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Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project

Current and Advanced Act Control System Definition Study, Summary Report

Staff of Boeing Commercial Airplane Company

NASA

FEDD DOCUMENT

NASA Contractor Report 3545

Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project

Current and Advanced Act Control System Definition Study, Summary Report

Staff of Boeing Commercial Airplane Company
The Boeing Commercial Airplane Company
Seattle, Washington

N∧S∧

National Aeronautics
and Space Administration

Scientific and Technical
Information Branch

1982

FOREWORD

This document summarizes the Current Technology ACT Control System Definition and the Advanced Technology ACT Control System Definition Tasks of the Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project, one element of the NASA ACEE/EET Project. The report covers work performed from July 1978 through October 1980 under Contracts NAS1-14742 and NAS1-15325.

The NASA Technical Monitors for these contract tasks were R. V. Hood and D. B. Middleton of the Energy Efficient Transport Project Office at Langley Research Center.

The work was accomplished within or under the direction of the Preliminary Design and the Engineering Technology Departments of the Vice President-Engineering organization of the Boeing Commercial Airplane Company. Key contractor personnel who contributed were:

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During this study, principal measurements and calculations were made in U.S. customary units and were converted to Standard International units for the final report of this work.

Use of trade names or names of manufacturers in this report does not constitute an official endorsement of such products or manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

CONTENTS

SUMMARY

This report summarizes the Current and Advanced Active Controls Technology (ACT) Control System Definition Study Task of the Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project. Prior assessment of fuel savings for ACT, in combination with increased wing aspect ratio, has shown as much as a 10% reduction in block fuel based on a current technology ACT system implementation. The IAAC control systems work covered by this report was designed to increase confidence in the means of implementing ACT functions. The work was accomplished under two tasks: **Current Technology ACT Control System Definition** and **Advanced Technology ACT Control System Definition.**

The **Current Technology ACT Control System Definition Task** objectives were to (1) define a highly reliable, low-technical-risk ACT control system for the IAAC airplane configurations using current technology; (2) support assessment of the benefit associated with the ACT airplane by evaluating reliability, cost, and weight of the current technology system; and (3) identify technical risk areas and recommend system development and testing.

This system architecture work addressed implementation of all potentially beneficial ACT functions, not just those employed on a particular airplane configuration. The approach was to define and evaluate two extreme system architecture forms, then define a "Selected System" that used the best features of the extreme forms. The Selected System employs three redundant digital computers to implement all of the ACT functions, four redundant smaller computers to implement the crucial pitch-augmented stability function, and a separate maintenance and display computer. The system reliability objective of probability of crucial function failure of less than 1×10^{-9} during a 1-hr flight can be met with current technology system components, if the software is assumed fault free and coverage approaching 1.0 can be provided. There is no generally accepted method to prove the software to be error free. However, a disciplined approach has been shown to be both essential and effective in producing highly reliable real-time control software.

The **Advanced Technology ACT Control System Definition Task** objectives were to (1) synthesize the ACT control laws directly, using optimal control theory; (2) evaluate the effects of actuation system nonlinearities on gust-load alleviation and flutter-mode control; and (3) determine a 1990 advanced technology ACT control system architecture.

The optimal approach to ACT control law synthesis yielded comparable control law performance much more systematically and directly than the classical s-domain approach. Certain high-frequency gust-load alleviation functions may require increased surface rate capability. Finally, the use of bus architecture with advanced computers (both potentially available circa 1990) appears to offer significant savings in airplane weight and cost.

The results of the Current and Advanced Technology ACT Control System Definition Tasks, summarized in this report, show that it is feasible to implement ACT with a cost-effective system. However, several major concerns—system complexity, system fault tolerance, redundancy management, and ACT function performance in the presence of system failures—remain unresolved. These concerns need to be examined through design and test work that provides an opportunity to experiment with and demonstrate specific system software and hardware. The IAAC Project should undertake these objectives and proceed into the Test and Evaluation element of the project plan.

INTRODUCTION

Although active controls have been used in several past commercial transports, those applications were either very limited in scope or were added after the airplane was in production to overcome an unanticipated difficulty or to add capability to the airplane. Considerable evidence suggests that the greatest benefit of ACT will result from incorporating ACT early in the design process. However, the expected benefit lacks credibility because there have been no major applications of ACT.

The first objective of the IAAC Project was to assess the benefits of a commercial ACT transport. During this benefit assessment, certain technical risk areas became clear. This led to the second objective of the IAAC Project, which was to identify technical risk areas and to recommend appropriate test and development programs. The final objective, to pursue resolution of these risk areas to the maximum possible extent within project resource limitations, is the focus of the current IAAC Project work.

IAAC PROJECT

The IAAC Project, part of the NASA/Boeing Energy Efficient Transport (EET) Program, has been organized into three major elements, as discussed in Reference 1 and shown in Figure 1. The first, Configuration/ACT System Design and Evaluation (fig. 1(a)), addressed the design of an ACT transport in sufficient detail to clearly identify the performance and economic benefits associated with the use of ACT. These airplanes incorporated all beneficial ACT systems, with current technology implementation assumed. This low-technical-risk approach (systems viewpoint) upheld the credibility of the overall ACT evaluation. Details of the airplane design and performance assessment are contained in the Initial ACT Configuration Design Study and Wing Planform Study reports (refs 2, 3, 4, and 5). The Current Technology ACT Control System Definition Task (cross-hatched part of fig. 1(a)) is summarized in this report.

The second element, Advanced Technology ACT Control System Definition (fig. 1(b)), has identified potential improvements through use of optimal control law synthesis techniques (Advanced System Trade Studies) and advanced technology components for the implementation of ACT systems (Implementation Alternatives) and will address ACT/Control/Guidance System and Demonstration ACT System Definition. The Advanced System Trade Studies and Implementation Alternatives are summarized in this report.

The final major element, Test and Evaluation, will begin work to reduce selected real or perceived technical risks associated with implementation of ACT.

ACT CONTROL SYSTEM STUDY

A modern Conventional Baseline Configuration, without any significant application of ACT, was required to determine the benefits of ACT and to establish the design mission for the ACT configurations. Except for ACT, the technology of the ACT airplanes designed under this project was fixed at the level established by the Baseline Configuration.

The airplane configuration design work proceeded under the assumption that any beneficial ACT function could be implemented with appropriate reliability and availability. The Current Technology ACT Control System Definition Task and the Advanced Technology ACT Control System Definition Task explored the means of implementing these functions. Details of the work are contained in the study final report (ref 6).
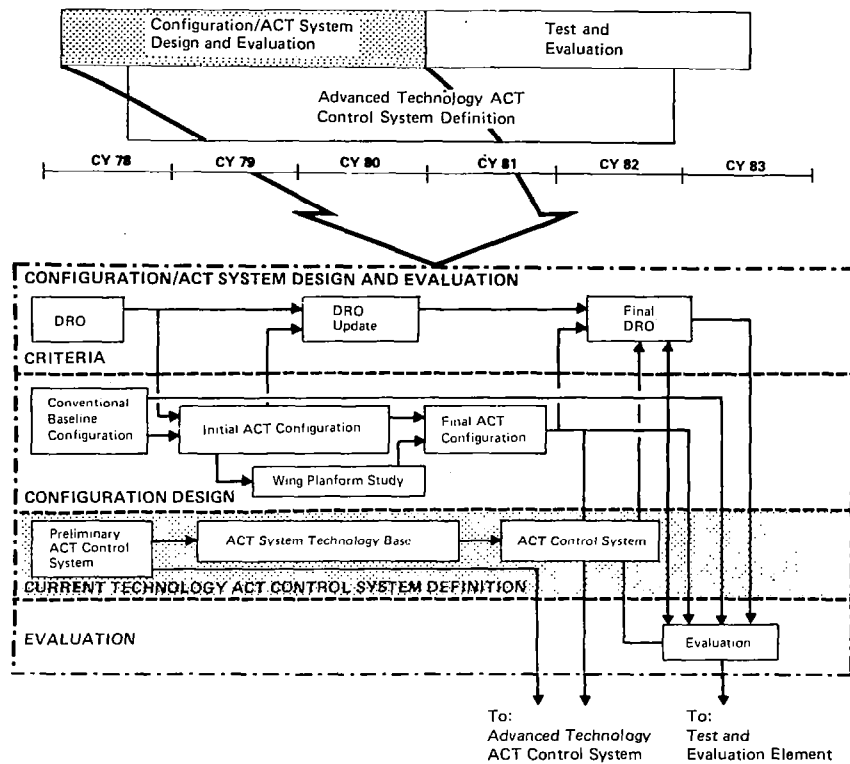
(a) Configuration/ACT System Design and Evaluation Element
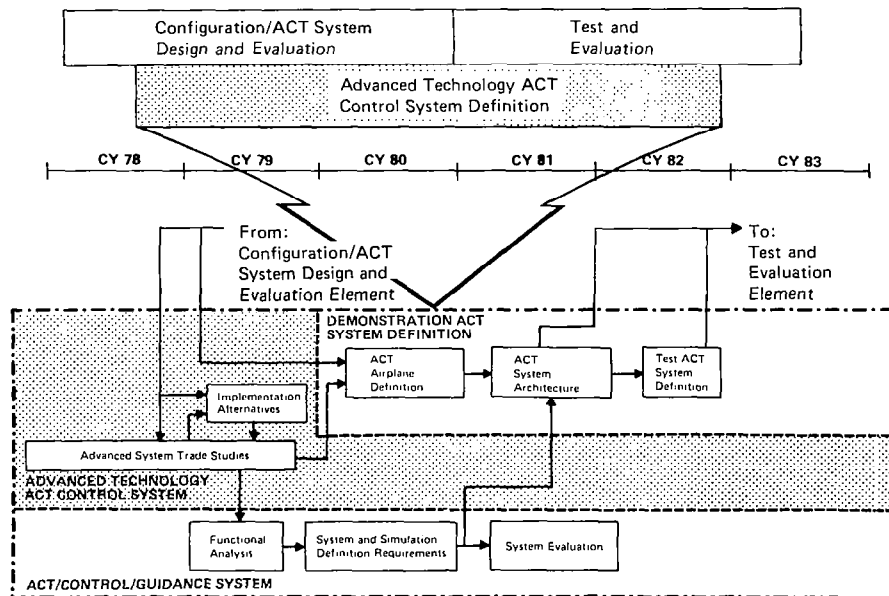
(b) Advanced Technology ACT Control System Definition Element

Figure 1. IAAC Project Plan

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ACT CONTROL SYSTEM REQUIREMENTS

ACT FUNCTIONS AND RELIABILITY

Because the controls work was proceeding in parallel with the active control airplane development reported in References 2, 3, 4, and 5, it was not possible to develop the control system for a single specific airplane. To ensure that the control system resulting from this work would support any beneficial active control function, as determined from the airplane work, the ACT functions to be implemented were selected as an all-inclusive set. The IAAC ACT airplane development studies have identified significant performance benefits of reduced pitch stability, and the ACT airplanes were configured with no requirement for unaugmented airframe stability. This in turn led to a requirement for a crucial pitch-augmented stability (PAS) system. None of the other ACT functions required, or could show benefit from, this degree of criticality. Table 1 lists the functions that were selected for this task and also shows the reliability requirement for each function expressed in terms of probability of failure during a 1-hr flight.

Early in the design of a commercial transport, the design requirements and objectives (DRO) that the airplane must meet are established. These requirements and objectives include the specific mission that the airplane must perform, the methods of design and analysis that will be used to design and build the airplane, and the characteristics that will be required of the systems in normal and failed modes for the airplane. These criteria are typically assembled into a document that is entitled "Design Requirements and Objectives (DRO)." Incorporating active controls into the design of a commercial transport necessitated some revisions of and new parts in the DRO. Incorporating ACT impacts the requirements relating to flight control system design, flying qualities, and—to a lesser extent—structural design, hydraulic, and electric power systems. These elements of the DRO that needed to be changed are reported in Appendix A of Reference 2. The control systems work summarized in this document was intended to produce systems that complied with this active controls DRO.

Determination of the criticality of any particular ACT function is made in terms of the impact on the airplane's operability following the loss of that function. Therefore, the criticality (crucial or critical) is interpreted in terms of a reliability requirement for the design of the system. Federal Aviation Regulation (FAR) Part 25 (ref 7) requires that the occurrence of any failure condition, which would prevent the continued safe flight and landing of the airplane, be "extremely improbable." A draft Federal Aviation Administration (FAA) Advisory Circular (ref 8) indicates that extremely improbable should be interpreted as a probability of failure less than 1×10^{-9} during a 1-hr flight. Figure 2 is reproduced from Reference 8. This figure was instrumental in the selection of the reliability requirement probability of failure being less than 1×10^{-9} during a 1-hr flight for the short-period PAS ACT function.

Table 1. Assumed ACT Function Criticality and Reliability Requirements

	Criticality	Reliability requirement, probability of failure during a 1-hr flight
Pitch-augmented stability, short-period (PAS$_{SHORT}$)	Crucial	10^{-9}
Pitch-augmented stability, speed (PAS$_{SPEED}$)	Critical	10^{-5}
Angle-of-attack limiter (AAL)	Critical	10^{-5}
Lateral/directional-augmented stability (LAS)	Critical	10^{-5}
Gust-load alleviation (GLA)	Critical	10^{-5}
Maneuver-load control (MLC)	Critical	10^{-5}
Flutter-mode control (FMC)	Critical	10^{-5}

Consequence of failure condition
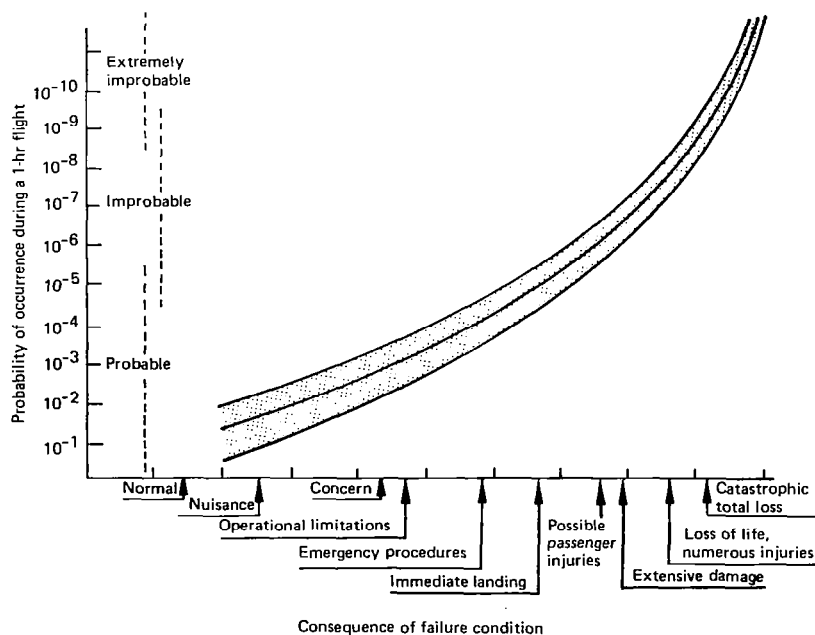
Figure 2. Relationship Between the Consequence of Failure and the Probability of Occurrence

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ACT CONTROL SURFACES AND SYSTEM SENSORS

A principal measure of success with respect to design of the ACT system is the resulting system reliability. To calculate that reliability, specific system components and aerodynamic surfaces must be selected. As previously described, this control system implementation task was not tied to a specific airplane but rather to an airplane that uses a number of possible ACT functions. In support of that approach, aerodynamic surfaces were assigned to each of the functions assumed, as shown in Figure 3(a). With the exception of the flaperons, all of the surfaces are hydraulically actuated aerodynamic plain flaps. The rudders and elevators are dual-hinged surfaces to provide more control power in a given surface area. The only unusual surfaces are the flaperons, mid-span and inboard, which use a plain flap (aileronlike) segment at the trailing edge of the high-lift system flaps. These surfaces are faired (i.e., fixed) whenever the high-lift system is deflected. Their purpose as active control surfaces is to deflect in high-speed flight with the flaps at zero deflection. As shown in the figure, stick-pusher actuation occurs at the column, which in turn commands the appropriate elevator deflection to limit the angle of attack.

To complete the system design, specific sensors were selected and placed in the airplane as shown in Figure 3(b). Again, because reliability is such an important characteristic, the sensors are conventional and as simple as possible. Note the considerable dependence on accelerometers, with limited dependence on angular rate sensors.

Single-surface, dual-
hinged elevator (PAS,
MLC, AAL)

Split outboard ailerons
(same total area as
Baseline)

Horizontal
stabilizer
(PAS)

Dual rudder
(LAS)

Flaperons (WLA)

Outboard aileron,
outboard segment
(WLA and existing
lateral control at
low speed)

Stick
pusher
(AAL)

Outboard aileron, inboard
segment (WLA, FMC, and
lateral control at low speed)
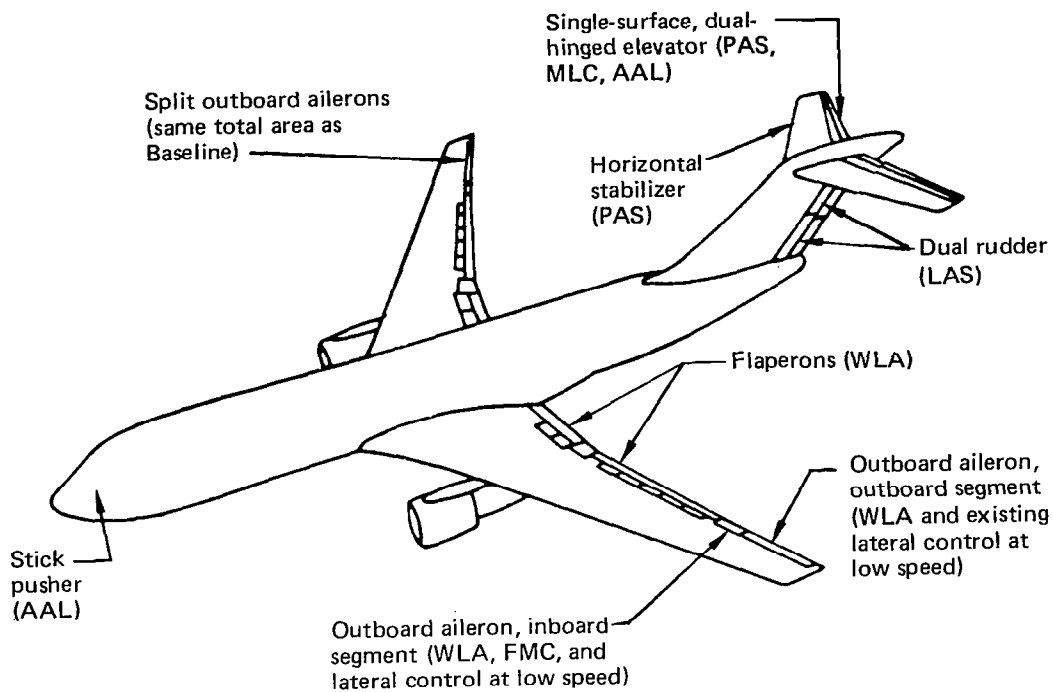
(a) Assumed Active Control Surfaces

Elevator*

Stabilizer*

Vertical acceleration

Rudder*

Pitch rate at
center of gravity

Control column
force

Flaperon inboard*

Flaperon midspan*

Outboard aileron, inboard
segment*

Angle of
attack

Vertical acceleration
at center of gravity

Outboard aileron, outboard
segment*

Airspeed

Yaw rate

Vertical
acceleration

*Position feedback sensors
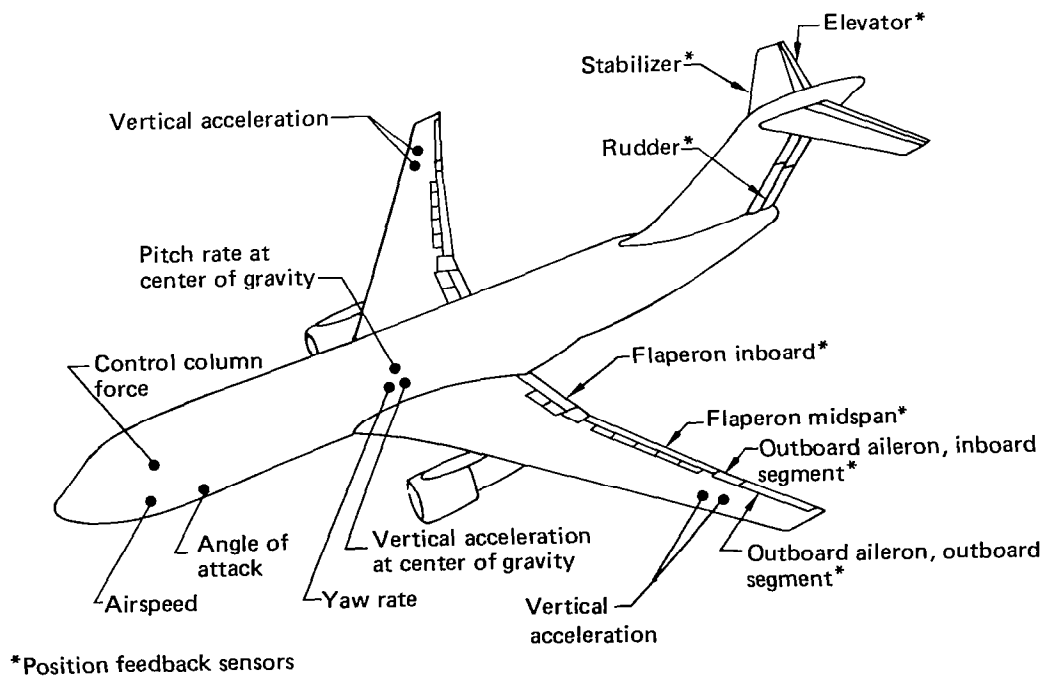
(b) ACT Sensor Placement

Figure 3. ACT Control Surfaces and Sensors

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CURRENT TECHNOLOGY ACT CONTROL SYSTEM DEFINITION

TASK OVERVIEW

An important element of the IAAC Project was the determination that the necessary active control functions could be implemented in a low-technical-risk system, which is an important adjunct of the overall ACT objectives. This led to selection of a ground rule for the current technology system work that only system elements or components that are available at this time would be considered for implementation of the active control system. It was recognized that this might lead to systems of somewhat higher weight or potentially higher cost of ownership. However, it was judged that the system weight and the system cost of ownership would not offset an apparent benefit from fuel savings and associated performance improvements. Therefore, this work proceeded under the ground rule that only those components and system elements that are proven today would be considered for implementation of the ACT functions.

The initial task of the Current Technology ACT Control System Definition work, as shown in Figure 1(a), was to postulate a preliminary ACT control system. During this subtask, it was determined that a predominantly digital system would best provide the many-faceted functions and associated redundancy management. A key element of this decision was the recognition that system self-test can be much more readily implemented in a digital architecture than in an analog architecture. Therefore, this work has proceeded under the assumption that the primary means of computation will be digital.

The approach to the design of a current technology system with the appropriate reliability requires at the outset a determination of how system reliability and cost of ownership varied with system form or architecture. This was accomplished (fig. 4) by designing systems with two rather extreme system forms; i.e., an Integrated System and a Segregated System. The distinguishing characteristic of these extreme forms is organization of the digital computers. An Integrated System, in the context of this study, means that all ACT functions are accomplished in a single set of digital computers, which does not mean to imply that all of the computers are doing identical tasks. Rather, because the required redundancy varies from ACT function to function, the total computer redundancy level was dictated by the most demanding function; i.e., short-period PAS function. The less demanding functions were distributed among the computers in the most efficient form possible. The counterpoint to an integrated architecture is the segregated architecture. Segregated, as used in this work, needs to be distinguished from distributed. A distributed system would mean that physically the elements of the system are distributed throughout the airplane. Segregated means that each function is assigned to a specific set of digital computers. Note that these digital computers typically would be smaller than those used in the Integrated System, but many more would be required.

The design and analysis of these alternative forms led to the Selected System, the principal output of this task, which combines some of the best features from both the Integrated and Segregated Systems. Several special studies supported the specific system design and evaluation as shown in Figure 4. The Selected System is a way to meet the system reliability objective, assuming the software is fault free and coverage approaching 1.0 can be provided.

SPECIAL STUDIES

FLAPERON ACTUATION	PITCH FLY BY WIRE

RELIABILITY PREDICTION METHODS

RULES

Objectives
ACT functions
Criticality
Reliability required
Safety required

SYSTEM

Integrated System

Segregated System

Selected System

EVALUATION

Reliability evaluation
Cost of ownership

OPERATION

Dispatch and in-flight operability
Controls and displays
Test and maintenance

COMPONENTS

Computers
Software
Actuators
Sensors

Figure 4. Current Technology System Task Overview

ACT SYSTEM ARCHITECTURE DEVELOPMENT

Integrated System Configuration

The keystone of the Integrated System is the set of four ACT computers that performs all ACT functions, system self-tests, and redundancy management. Figure 5 shows a top-level view of those computers and their relation to other system elements. Consistent with the low-technical-risk theme of this work is the manner in which the ACT system meshes with the balance of the airplane control system. The Baseline Airplane has a triplex digital air data computer (DADC) and a triplex inertial reference system (IRS). These systems became major sensors for the ACT system but were not sufficient to provide all of the information necessary for the many ACT functions. For example, the crucial short-period PAS function requires four pitch-rate signals. After examining the alternatives, an independent, single pitch-rate sensor was added to the system to provide a total of four pitch-rate signals, with the remaining three coming from the IRS. The other ACT sensors are accelerometers and column sensors necessary to accomplish the various functions.

Control of the airplane occurs through the aerodynamic surfaces illustrated in Figure 3(a); these surfaces are in turn signaled as shown in the right half of Figure 5. Note that the mechanical control system was retained by using secondary servos to add the ACT commands into the mechanical control path. This is not meant to imply that this is either the most reliable or most desirable system form, but it was felt at the time to be the least controversial means of altering the control system.

The new active control surfaces (inboard flaperons, outboard flaperons, and the inboard segment of the outboard aileron) are electrically commanded, hydraulically actuated surfaces. Because it was necessary to add new actuators to power the surfaces, electrically commanded actuators were selected.

Pilot and autopilot inputs are provided to the primary actuators exactly as in the Baseline Airplane.
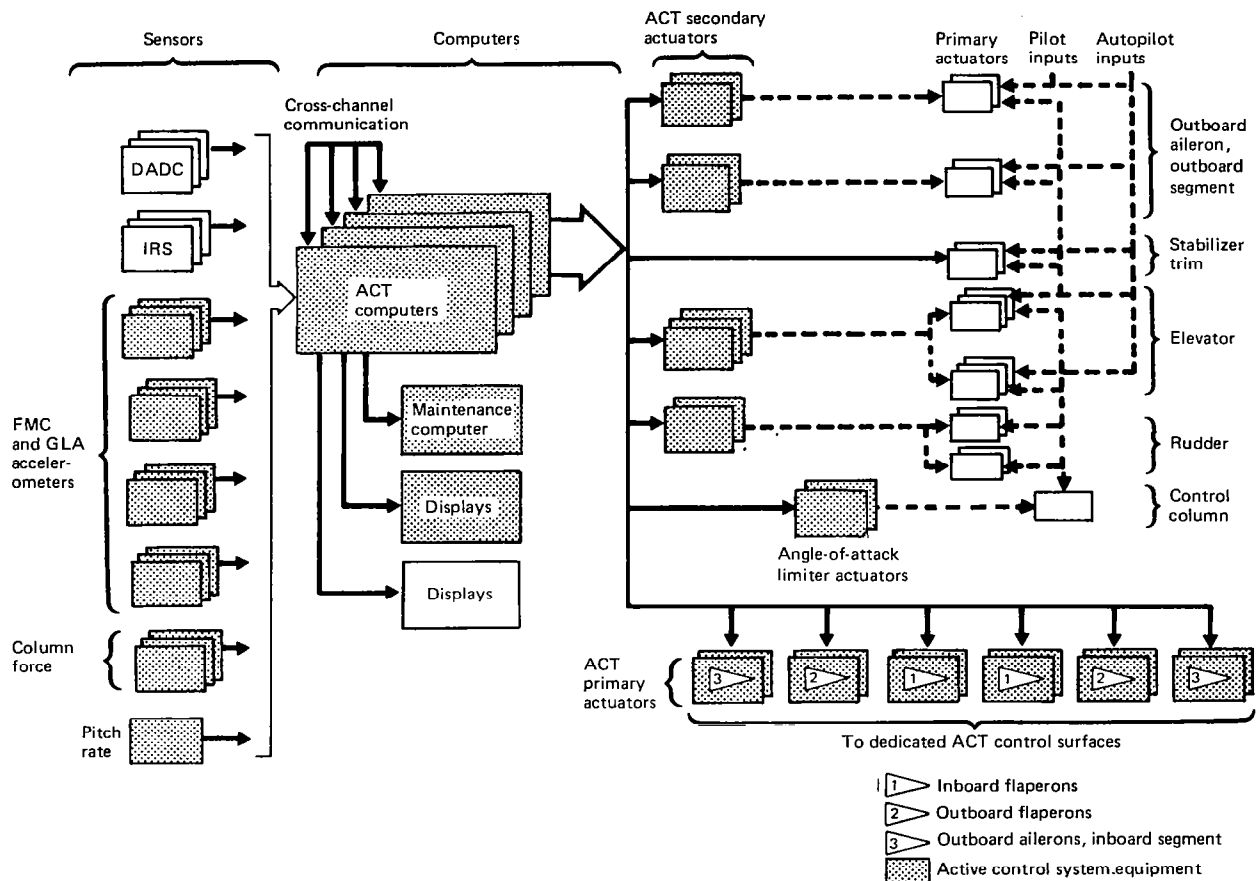
Figure 5. Integrated System Configuration

Segregated System Configuration

The principal difference between the Integrated and Segregated Systems (fig. 6) is the substitution of 21 separate computers for the 4 ACT Primary Computers and 1 maintenance computer of the Integrated System. These 21 computers, arranged as shown in the figure, accomplish each separate ACT function and redundancy management of the total system.

The only change to the sensors is the addition of three additional pitch-rate sensors, for a total of four, dedicated to the short-period PAS augmentation task. This change was made by removing the inertial reference system from that control path to increase the crucial function reliability. The output side of the system has the same number of secondary actuators summed similarly into the mechanical system and the same number of electrically signaled primary actuators as the Integrated System.
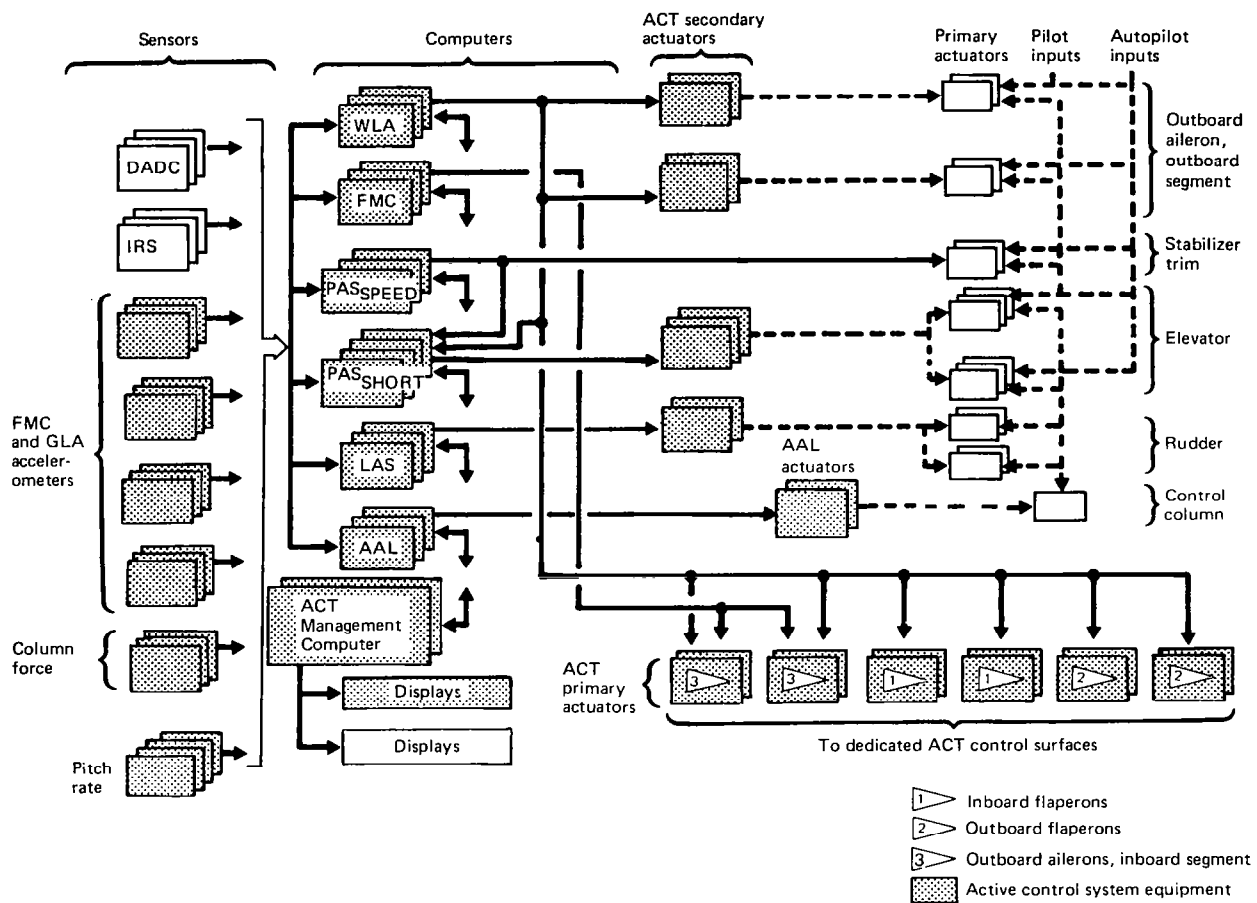
Figure 6. Segregated System Configuration

System Comparison

An expectation of the Segregated System configuration was improved reliability. It was expected that the Segregated System cost would be greater than the Integrated System cost. However, a key factor was whether the cost increased faster than the reliability increased; in other words, what happened to the return on investment (ROI). The first two columns in Table 2 compare the Integrated System and Segregated System principal characteristics and probability of failure during a 1-hr flight with the impact on airplane operation. This impact appears as either continuing the flight with restricted flight envelope, a necessity to divert, or a dispatch delay. The impact of any particular failure, of course, depends on the ACT function that is degraded or lost and its impact on the airplane.

The two systems used the same assumed computer reliability. The probability of restricted flight did not improve as expected. The probability of flight diversion and dispatch delay did improve with the Segregated System compared to the Integrated System. The Segregated System was almost 50% more expensive than the Integrated System, which resulted in a decrease in the expected return on incremental investment. Careful consideration of the reasons for this decline in reliability, as reflected in the probability of restricted flight, highlighted the sensor set as the primary cause of the decline. The heavy dependence of the ACT functions on the output of the DADC, combined with the increased parts count in the greater number of computers, led to a decline in reliability. An examination of the attributes of these two systems led to the definition of the Selected System, shown in column three in Table 2, which combines some of the best features of the previous two systems. The Selected System has better overall reliability than the Integrated System, at about the same cost, and almost the same return on incremental investment. The expected airplane performance benefit that is reflected in the return on incremental investment calculations is based on the Initial ACT Configuration (ref 2), adjusted for differences in the ACT systems.

Table 2. Comparison of Integrated, Segregated, and Selected Systems

System / Item	Integrated System	Segregated System	Selected System
Computer weight	4 control computers at 11.3 kg (25 lb) each Total: 45.4 kg (100 lb)	19 control computers at 6 kg (13.25 lb) each 2 management computers at 2.7 kg (6.0 lb) each Total: 119.6 kg (263.8 lb)	3 ACT Primary Computers at 1 (25 lb) each 4 Essential PAS Computers at ((13.25 lb) each 1 ACT Maintenance and Displa Computer at 2.7 kg (6 lb) Total: 60 kg (134 lb)
Memory requirement	32K read-only memory (ROM) and 2K random-access memory (RAM) (128-word 8-bit non-volatile memory for maintenance information)	16K ROM and 64- to 512-word RAM for control computers plus 32K ROM and 1K RAM and 128-word 8-bit nonvolatile for management computer	24K ROM and 2K RAM per ACT Primary 11K ROM and 256-word RAM per Essen 32K ROM and 1K RAM and 128-word, 8
Computer reliability (assumed)	6800-hr mean time between failures (MTBF)	6800-hr MTBF	6 800-hr MTBF for ACT Primar 12 000-hr MTBF for Essential PA
Probability of restricted flight	2.5×10^{-3} per 1-hr flight	3.3×10^{-3} per 1-hr flight	1.7×10^{-3} per 1-hr fligh
Probability of flight diversion	7.1×10^{-4} per 1-hr flight	2.6×10^{-4} per 1-hr flight	4.0×10^{-4} per 1-hr fligh
Probability of dispatch delay	3.8×10^{-4} per dispatch	1.6×10^{-4} per dispatch	1.2×10^{-4}
Increment cost per airplane (to airline)	$274 000	$390 000	$297 100
Expected return on investment	25.1%	22.8%	24.6%

Selected System Configuration

The form of the Selected System (fig. 7.) results from the decision to accomplish the critical ACT functions and Full PAS function in a triplex set of primary computers. The Full PAS function provides good (level 1) handling qualities, but the triplex set cannot provide sufficient reliability to accomplish the crucial short-period PAS function; therefore, it is backed up by a quadruple set of essential computers. All communication to the elevator servos occurs through the Essential PAS Computers; i.e., the normal handling qualities pitch augmentation and the wing-load alleviation elevator commands are passed to the Essential PAS Computers and then on to the elevator secondary servos.

If a failure, or failures, are detected in the ACT Primary Computers that result in loss of the short-period PAS function, the ACT Primary Computers are taken out of that loop and the Essential PAS Computers provide a minimum (level 3) handling qualities pitch augmentation using the four dedicated pitch-rate sensors and the four Essential PAS Computers. These minimum handling qualities are judged sufficient to safely land the airplane but may not be sufficient to continue the mission as originally planned.
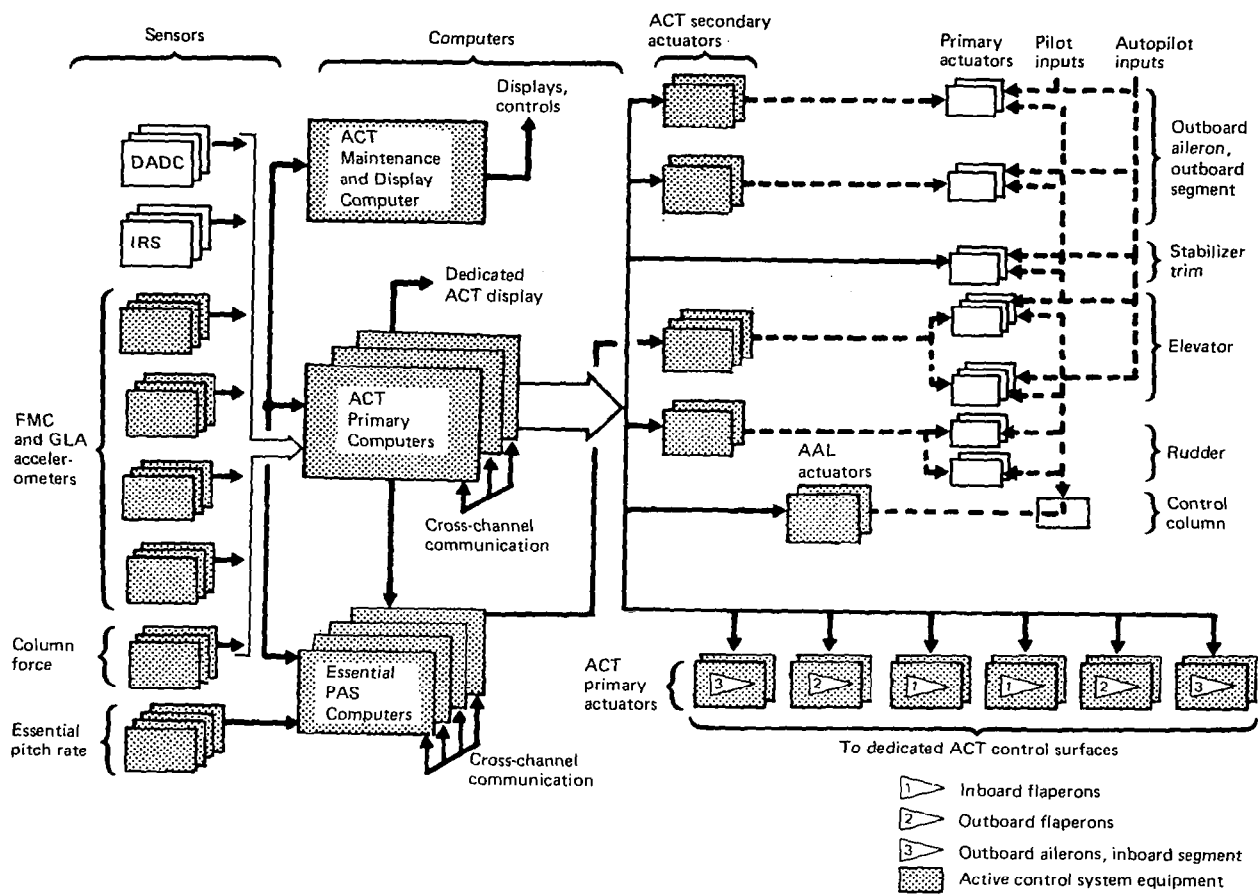
Figure 7. Selected System Configuration

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AIRPLANE SYSTEMS

Hydraulic Power System

The hydraulic power system consists of three 20 700-kPa (3000-lbf/in^2) systems identified as A, B, and C, as shown in Figure 8. Hydraulic power is generated in systems A and C by engine-driven pumps (EDP) installed in parallel with electric-motor-driven pumps (EMP). Hydraulic power is generated in system B from two ac-powered electric-motor-driven pumps and one air-turbine-driven pump (ATDP). The bleed air manifold is a pneumatic source supplied by the engines or the auxiliary power unit (APU).

Emergency hydraulic power is derived from wind-milling engines driving the engine-driven pumps. System A is augmented by a ram-air-turbine-driven (RAT) hydraulic pump.

With the airplane on the ground, hydraulic power is available from the APU, automatic ground carts driving the air-turbine-driven pumps, or from the ac electric-motor-driven pumps powered from either the APU, the ground carts, or by an external hydraulic power supply source. Flight deck controls and displays consist of depressurization switches, shutoff switches, low-pressure and low-fluid quantity warning lights, and a selectable system pressure and fluid quantity readout.

The maximum system flow requirements are only slightly greater than they would be for a nonactive control airplane and are shown in Figure 8. The several approaches to ACT system design, previously discussed, do not affect the hydraulic system design.
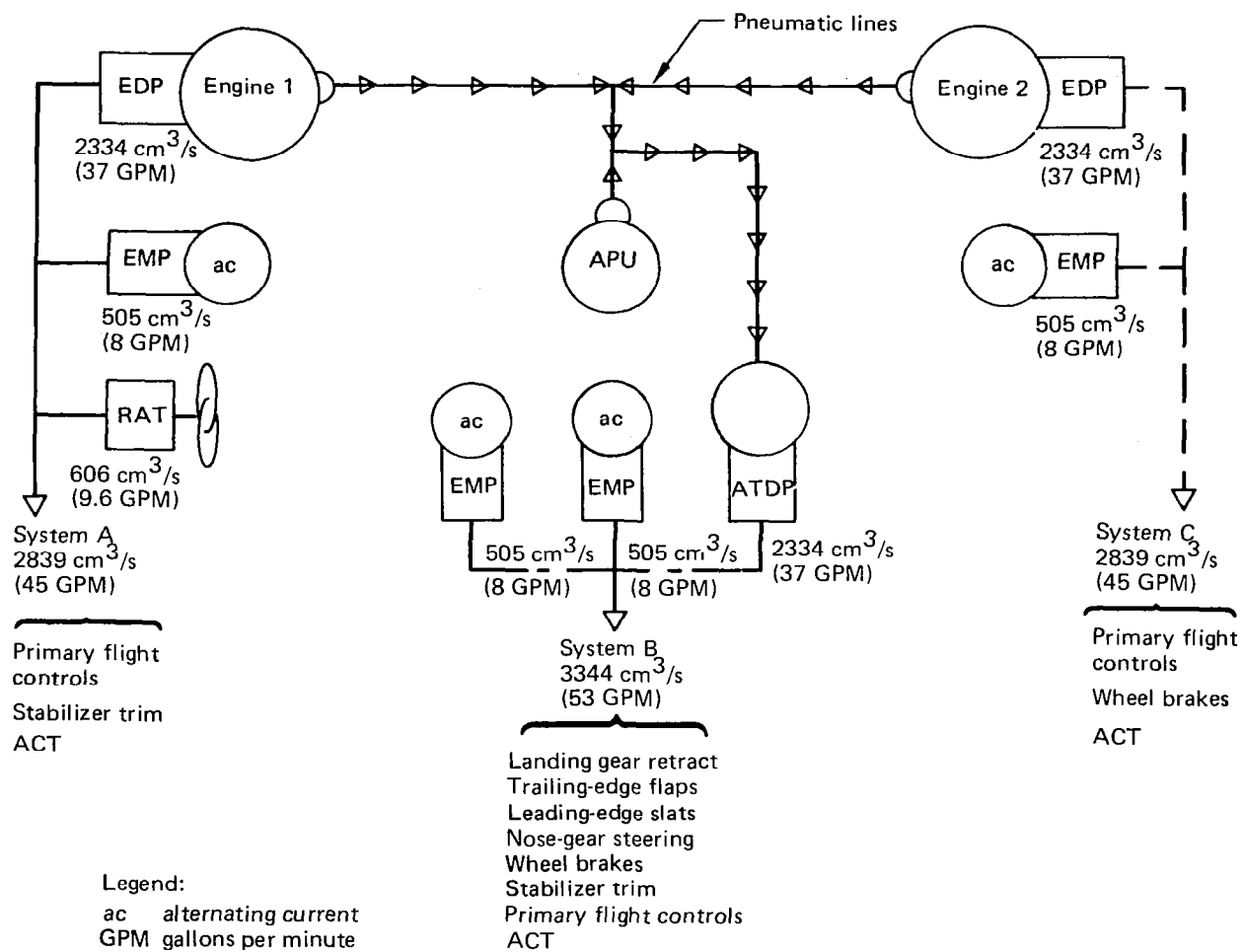
Figure 8. Airplane Hydraulic Power System

Electric Power System

The electric power system shown in Figure 9 is a three-phase, 115V, 400-Hz system supplied by two engine-driven, 90-kVA integrated-drive generators. These generators cannot be paralleled, so the system operates as two isolated channels. A third 90-kVA APU-driven generator is provided as an in-flight backup for the two main engine-driven generators and for ground maintenance operations. The APU can be started at any altitude up to 7620m (25 000 ft) and can provide full electric power up to 10 670m (35 000 ft).

Any single generator can supply all flight-essential loads. Two of the three generators must be operative for airplane dispatch without load reduction or for a category III landing.

Airplane 28V dc power is provided by two 120A unregulated transformer-rectifier (T-R) units. Each of the main ac buses supplies its own transformer-rectifier unit.

Backup power for flight-critical loads is supplied by a pair of nickel-cadmium batteries. Battery chargers provide controlled recharge of the battery and operate a transformer-rectifier unit to supply standby loads if the main dc source is lost but ac power is available.

ACT considerations required the addition of the equipment outlined in bold in Figure 9 to a system that was suitable for a conventional commercial transport. The principal difference is the addition of this second standby battery and charger to provide power for flight-critical ACT functions. The battery life, in such operation with no other electric power source available, is estimated to be 30 min.

Gen

GCB

External power

Gen | APU

Charger | T-R 3

Gen

GCB

EPC

APB

Main ac bus 1

BTB

BTB

Main ac bus 2

T-R 1 | Util 1

ac ground handling

T-R

Util 2 | T-R 2

ac bus 3

ac standby bus

Ground service transfer

Battery charger

Battery charger

Main dc bus 1

dc tie contactor

Main dc bus 2

ACT dc bus 1

dc bus 3

Hot battery bus 1

Hot battery bus 2

ACT dc bus 2

Standby inverter

Battery bus 1

Battery bus 2

ACT channel A

ACT channel B

ACT channel C

ACT channel D

Legend:
ac   alternating current
APB   auxiliary power breaker
APU   auxiliary power unit
BTB   bus tie breaker
dc   direct current
EPC   external power contactor
GCB   generator circuit breaker
Gen   generator

Change from Baseline Configuration

Figure 9. ACT Airplane Electric Power System

Primary Control System

Longitudinal—The longitudinal control system, consisting of elevator control and horizontal stabilizer trim, is illustrated in Figure 10. Each single-segment, dual-hinged elevator is powered by three parallel power control units (PCU). The pilot elevator command transmitted from the control column through the control cables to the aft quadrant is mechanically summed with the autopilot and ACT elevator commands.

Elevator command signals from the triplex ACT Primary Computers are connected to Essential PAS Computers A, B, and C. These signals are made available to all four Essential PAS Computers through cross-channel communication links. Three of the quadruple Essential PAS Computers command the triplex force-summed elevator secondary servos. In addition to the triple ACT elevator secondary servos, a servo mathematical model is programmed in the Essential PAS Computers—for comparison with actual servo performance—to provide the required fail-operational/fail-operational capability (i.e., the elevator command output from the servos continues after two servo failures) for short-period PAS.
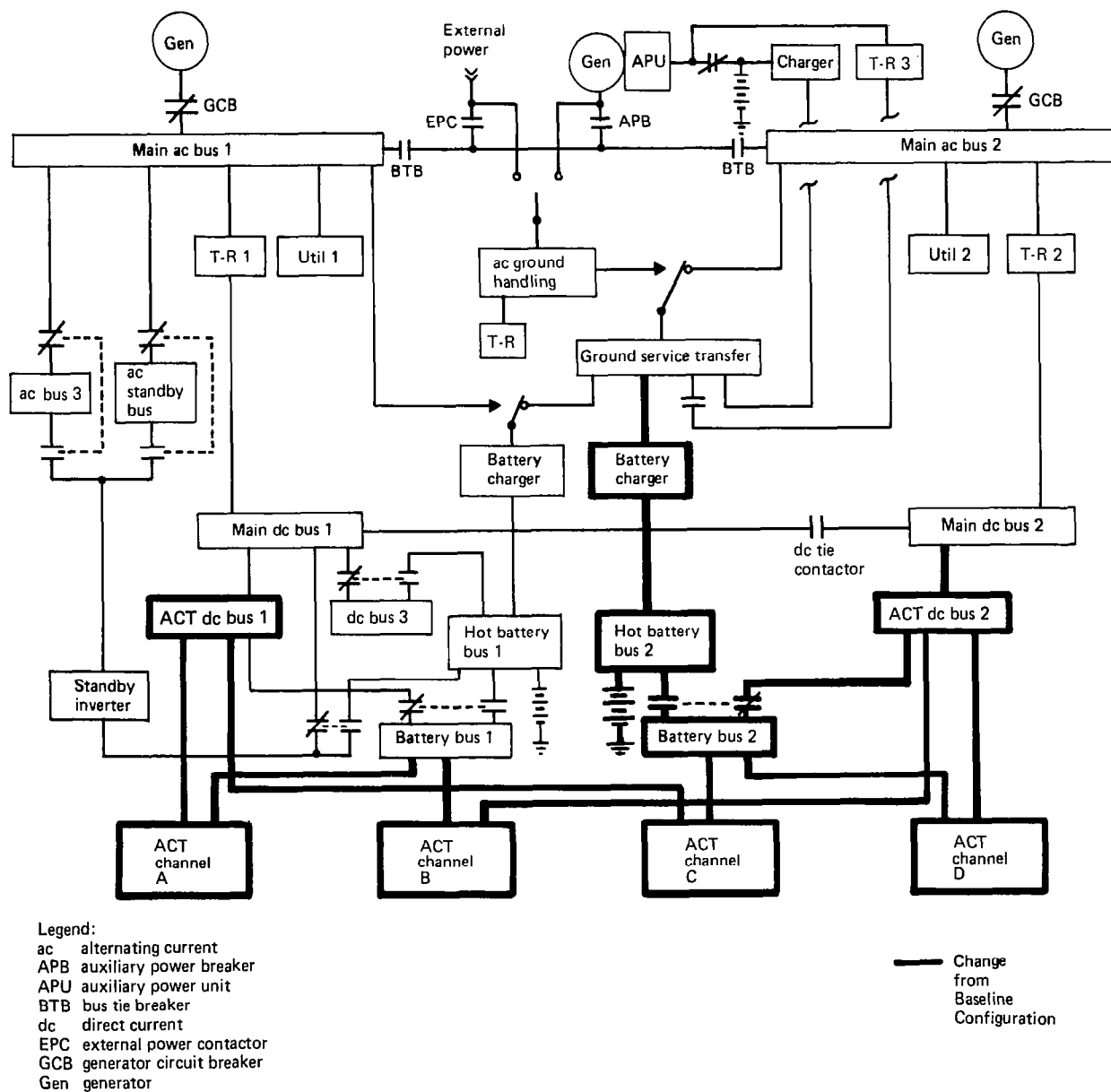
Lateral—The lateral control system consists of inboard ailerons, outboard ailerons (inboard and outboard segments), and 10 spoiler panels (5 on each wing) as shown in Figure 11. The pilot's commands are transmitted mechanically through cables to the central control actuator where they are summed with the autopilot commands and transmitted on to the inboard aileron. The inboard aileron position commands are summed with the output of the ACT aileron secondary servos to form the outboard aileron (outboard segment) command. The inboard segment of the outboard aileron responds to electrical commands, which are the sum of the pilot commands and the ACT commands. The spoilers respond electrically to pilot and autopilot commands. The baseline outboard aileron lockout signal from the control system electronic units (CSEU) removes the pilot lateral control command from the outboard aileron (outboard segment) PCUs at the lockout airspeed without affecting the WLA commands to this aileron.

The secondary servos and electrically commanded PCUs on the outboard aileron inboard segment are dual force-summed units. To provide adequate redundancy and fail-operational capability, mathematical models of these servos are programmed into the ACT computers and used in a manner similar to the elevator servo model.

Directional—The directional control system consists of two double-hinged rudders (fig. 12); each rudder is controlled by dual power control units. The rudder command is the sum of pilot commands, transmitted by cable to the aft quadrant, and the autopilot and ACT rudder commands. The required ACT system reliability is provided through dual force-summed secondary servos plus mathematical models implemented in the ACT Primary Computers to provide fail-operational capability.
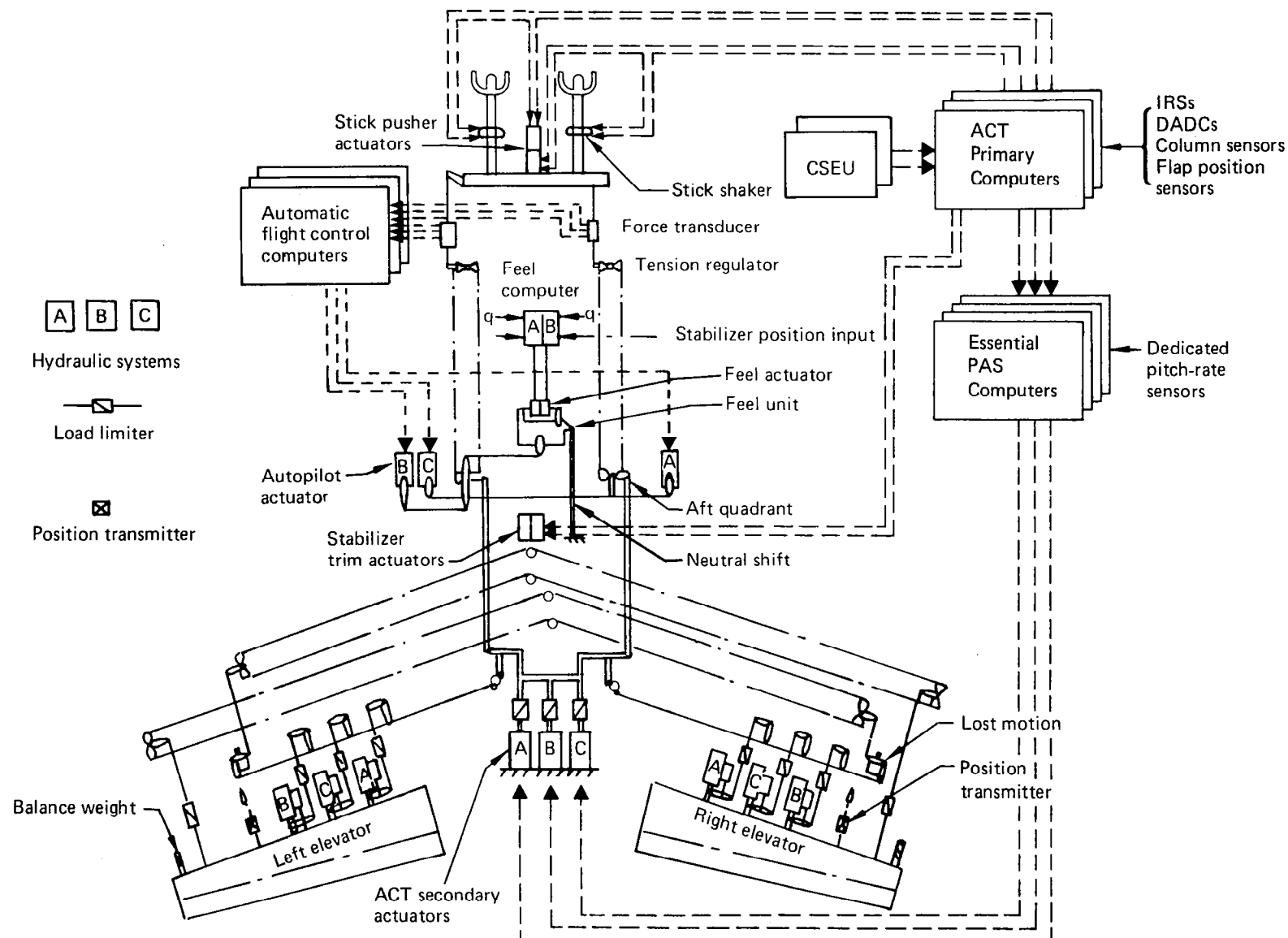
Figure 10. Longitudinal Control System
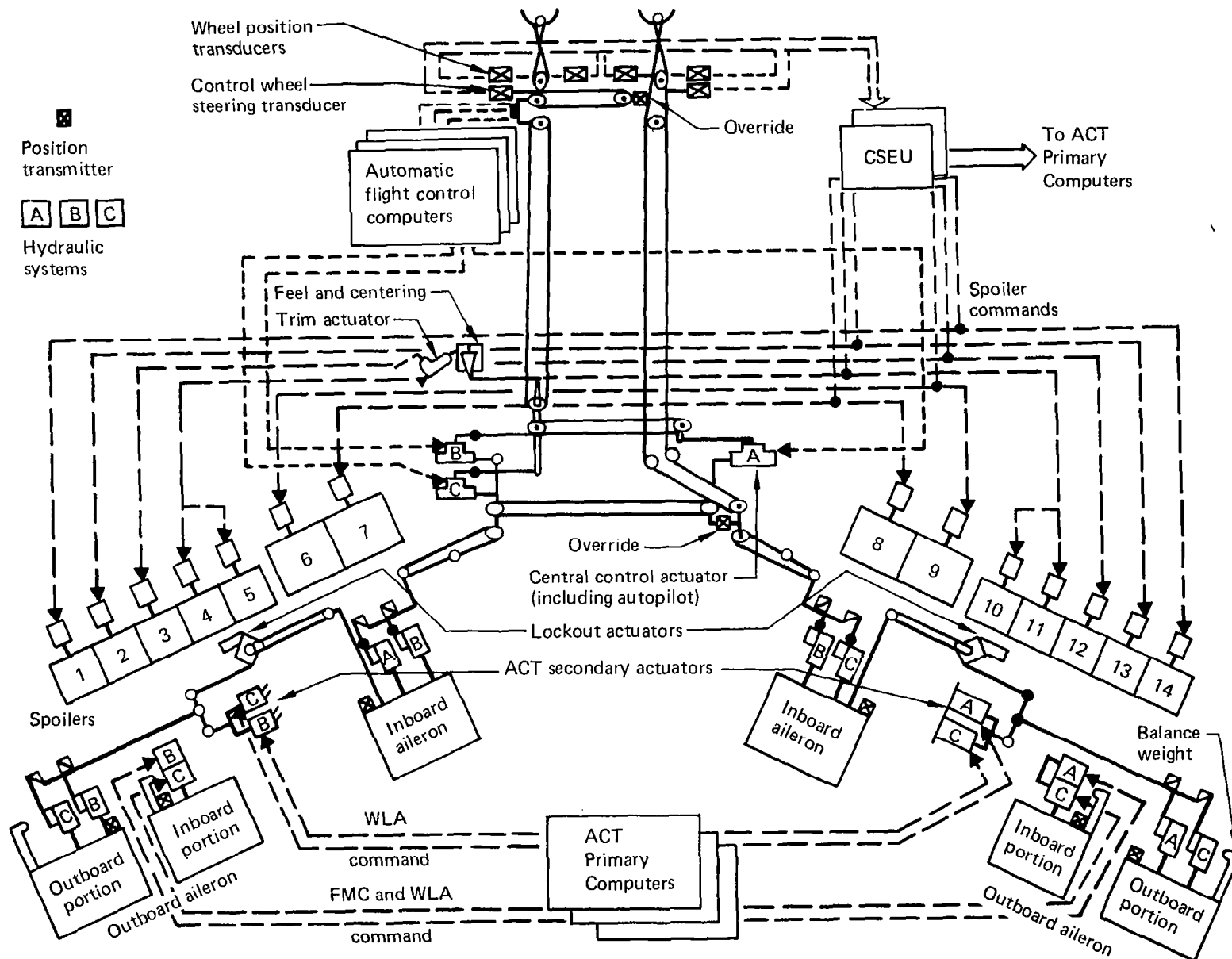
Figure 11. Lateral Control System

Wheel position transducers

Control wheel steering transducer

Position transmitter

A B C

Hydraulic systems

Automatic flight control computers

Override

CSEU

To ACT Primary Computers

Feel and centering

Trim actuator

Spoiler commands

B

C

A

6 7

Override

Central control actuator (including autopilot)

Lockout actuators

ACT secondary actuators

8 9

10 11 12 13 14

1 2 3 4 5

Spoilers

C B

B C

Inboard aileron

A B

Inboard portion

Outboard portion

Outboard aileron

WLA command

FMC and WLA command

ACT Primary Computers

B C

Inboard aileron

A C

A C

Inboard portion

A C

Outboard aileron

Outboard portion

Balance weight

24

Figure 12. Directional Control System

ACT FUNCTIONS

Full Pitch-Augmented Stability

The Full PAS control laws are implemented in the triplex ACT Primary Computers. Full PAS includes short-period and speed stability to provide good (level 1) pitch-axis handling qualities; i.e., equal to or better than a conventional transport airplane. Figure 13 is a block diagram of the Full PAS System.

Short-period PAS uses pitch-rate signals from the triplex inertial reference system sensors and control column sensors to generate the elevator command. The pitch-rate and column sensors are hardwired to specific ACT Primary Computers. Computer cross-channel communication includes sensor signals so that each computer has access to all sensor inputs. The feedforward and feedback gains of short-period PAS are scheduled as a function of airspeed. If the airspeed sensor fails, the gain schedule becomes dependent upon flap position signals. If the inertial reference system signals are lost, pitch-axis control deteriorates to a minimum acceptable level (level 3). However, the pilot will be able to continue to control the airplane with a combination of the remaining speed PAS and the Essential PAS System (described in the next section). The ACT Primary Computers transmit status information on short-period PAS to the Essential PAS Computers to enable timely engagement of the Essential PAS control law.

When elevator deflection exceeds a certain threshold value for more than a predetermined time, the elevator offload logic acts to adjust pitch trim by moving the horizontal stabilizer through the stabilizer trim interface in the CSEU. The CSEU trim function receives autopilot, pilot, and ACT trim inputs and selects an appropriate signal for stabilizer position.

Channel A
signals:

Pitch rate, q

Cross-channel
communication

Column position

Air data, ΔV

Stabilizer position

Elevator position

ACT Primary Computers

Pilot and autopilot
stabilizer commands

S
S
F
D

(SSFD applied
to each input
signal as above)

Stabilizer
position

Elevator
position

Offload
logic

F
D

Control system
electronic units
(CSEU)

Stabiliz
trim
actuato

St

q

$\dfrac{1}{s/10 + 1}$

KQ(V)

F
D

Column
position

$\dfrac{0.8}{s + 0.8}$

KC(V)

ΔV

$\dfrac{25\,s + 1}{5\,s + 1}$

KU(V)

Dedicated pitch
rate A, B, C, and D

Pilot and auto
elevator comm

Essential PAS
Computer
A

Elevator
secondary
actuator
A

Cross-channel
communication

Channel B
sensor inputs

ACT
Primary
Computer
B

Cross-channel
communication

Dedicated pitch
rate A, B, C, and D

Essential PAS
Computer
B

Elevator
secondary
actuator
E

Channel C
sensor inputs

ACT
Primary
Computer
C

Dedicated pitch
rate A, B, C, and D

Essential PAS
Computer
C

Elevator
secondary
actuator
C

Legend:
FD failure detection
KC servovalve monitor gain
KQ pitch-rate gain
KU speed gain
q   pitch rate
s   Laplace variable
SS signal selection

Dedicated pitch
rate A, B, C, and D

Essential PAS
Computer
D

Actuator
mathematical
models
(implemented i
the computers)

Figure 13. Full Pitch-Augmented Stability Block Diagram
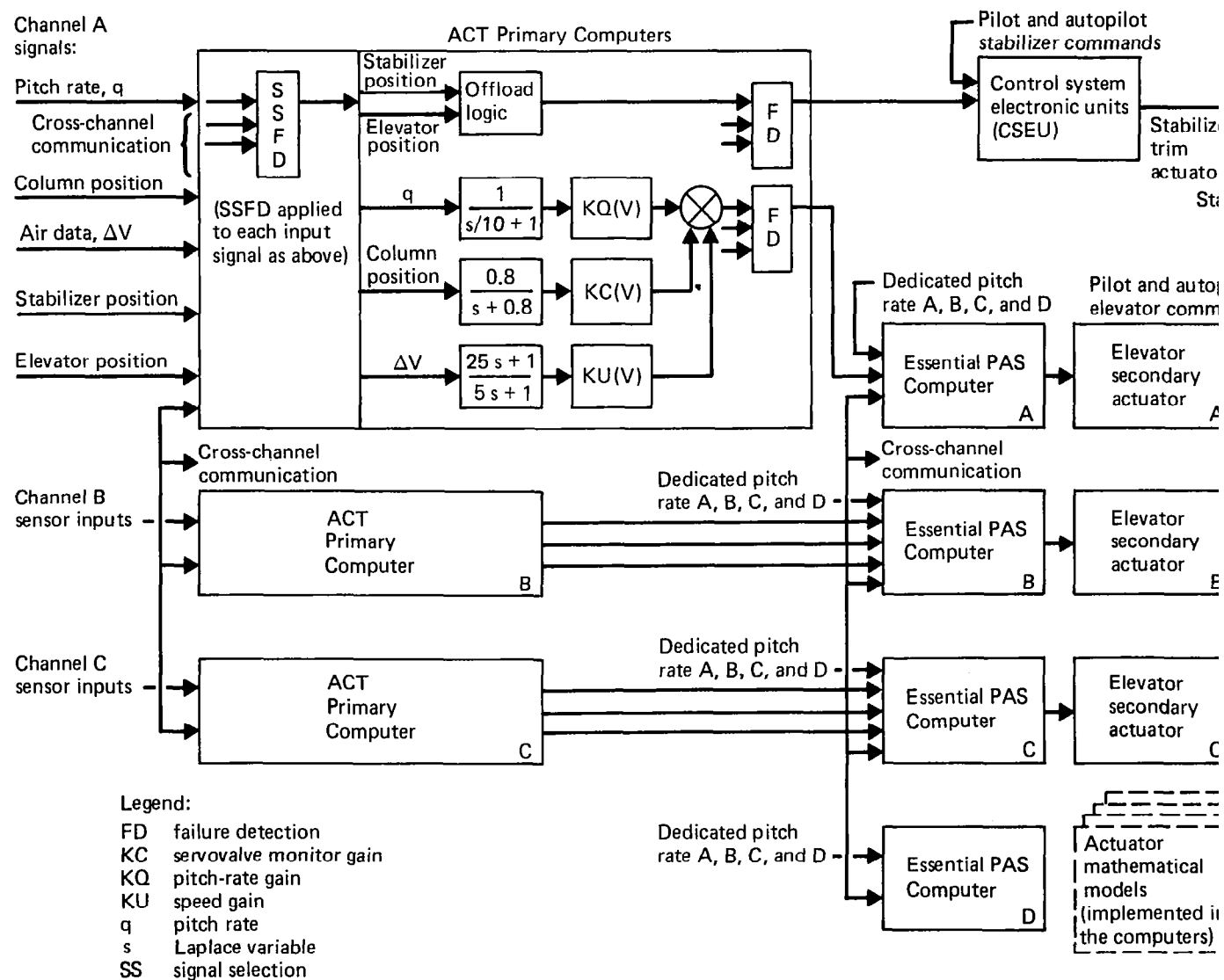
Essential Pitch-Augmented Stability

The Essential PAS control laws are implemented in the quadruple set of Essential PAS Computers. The Essential PAS System is a highly reliable, fixed-gain, short-period augmentation system that provides at least minimum acceptable handling qualities (level 3) in the pitch axis. Figure 14 is a simplified block diagram of the system. The system uses dedicated quadruple pitch-rate sensors, quadruple dedicated computers, and triple elevator secondary servos in conjunction with servo mathematical models in each of the quadruple computers.

The pitch-rate sensors are simple, highly reliable analog devices dedicated to the Essential PAS System. Each pitch-rate sensor is directly connected (hardwired) to all of the Essential PAS Computers. The consolidated pitch-rate signals are processed by the signal selection and failure detection (SSFD) algorithm to create a signal for control law computation and to monitor system failure status. The output of the Essential PAS control law is normally disconnected from the servocommand summing circuits. If the short-period PAS of the ACT Primary System fails, the fixed-gain short-period PAS shown in Figure 14 is introduced into the loop with an easy-on logic. The Full PAS and maneuver-load control (MLC) elevator commands of the ACT Primary System are processed by the SSFD to form a summed elevator command and to monitor failure status. To protect functional independence, elevator commands of short-period PAS, speed PAS, and MLC are processed separately by the SSFD algorithm.

Elevator command signals from the triplex ACT Primary Computers are connected to Essential PAS Computers A, B, and C and made available to all four Essential PAS Computers through cross-channel communication links. The Essential PAS Computers operate asynchronously. This feature has been shown to be satisfactory in laboratory tests. Three of the quadruple Essential PAS Computers command the triplex force-summed elevator secondary servos, as shown in Figure 14. The fourth Essential PAS Computer provides a servocommand and servo status for use in selecting the servocommand and/or shutting down a failed servo.
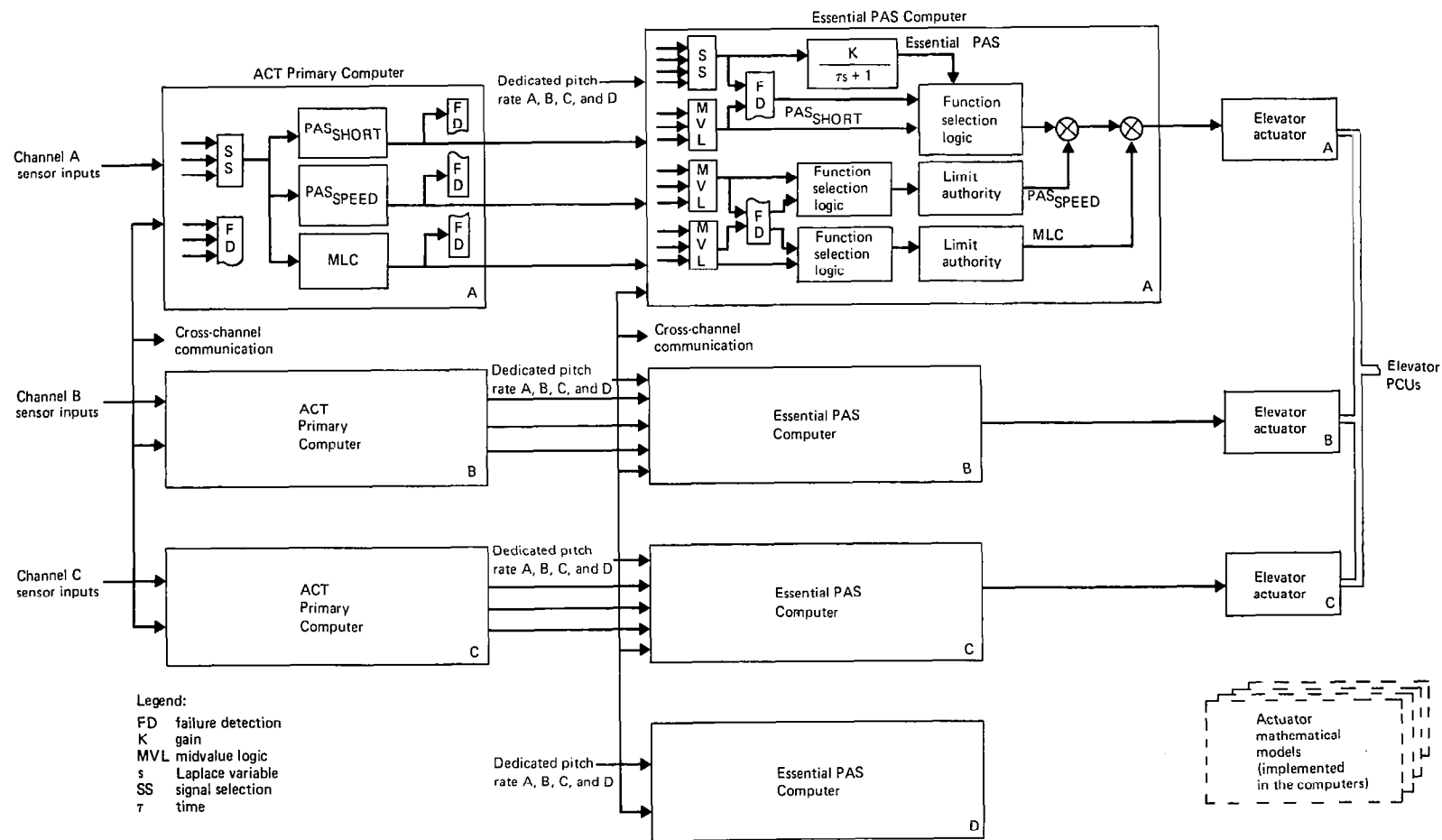
Figure 14. Essential Pitch-Augmented Stability Block Diagram

Legend:
FD   failure detection
K   gain
MVL   midvalue logic
s   Laplace variable
SS   signal selection
τ   time

29

Angle-of-Attack Limiter

The angle-of-attack limiter (AAL) function includes both warning (stick shaker) and limiting (stick pusher) functions. The AAL function is implemented in the triplex ACT Primary Computers. Figure 15 is a block diagram of the AAL system.

The stick-shaker and stick-pusher actions are functions of angle of attack (relative to a reference angle of attack) and the rate of change of angle of attack. These AAL reference points are a function of airplane leading-edge slat and trailing-edge flap position as well as airspeed. When the difference between the actual angle of attack and the stick-shaker reference angle of attack falls below a certain threshold, the stick shaker is activated to provide stall warning. The threshold is a function of how rapidly the airplane is approaching stall; i.e., if there is a large rate of increase in angle of attack, the threshold is lowered to further ensure that limiting occurs at or below the maximum allowable angle of attack.

If angle of attack continues to increase beyond that for warning, the stick pusher operates to apply an airplane nose-down force on the control column. The AAL stick-pusher actuator uses low-pressure air from the basic airplane engine bleed system and pressure from an accumulator as multiple power supplies to meet the fail-operational requirement. Actuation time of the stick-pusher actuator is approximately 0.2 sec.

The pilot may override the pusher by exerting sufficient force on the column or by operating a manual dump valve that directly vents actuator operating pressure.

ACT Primary Computer

Channel A signals:

Angle-of-attack limiter

Air data

Cross-channel communication

S
S
F
D

Angle of attack

Threshold

Stick shaker

F
D

Slat position

Flap position

Stabilizer

(SSFD applied to each input as above)

Maximum angle of attack

KA

Pitch rate

q

Filter

KQ

Air data

Cross-channel communication

Gain schedule

Threshold

F
D

A

Stick pusher

Channel B signals

ACT Primary Computer

B

Channel C signals

ACT Primary Computer

C

Legend:

FD   failure detection
KA   angle-of-attack gain
KQ   pitch-rate gain
q   rate of change of pitch attitude
SS   signal selection

Figure 15. Angle-of-Attack Limiter Block Diagram

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Lateral/Directional-Augmented Stability

The lateral/directional-augmented stability (LAS) function includes a conventional yaw damper and turn coordination and is implemented in the triplex ACT Primary Computers. Figure 16 is a block diagram of the LAS function.

Yaw rate and bank angle from triplex IRS and control wheel sensors are used to improve Dutch roll damping and reduce side-slip angle excursions. Air data signals from the triplex digital air data computers are used as gain schedule inputs to provide good (level 1) handling qualities. If the digital air data computer fails, LAS uses flap position as a backup gain schedule input.

The airplane can be dispatched, with restriction, with a single-channel LAS system operational because (1) LAS has adequate self-monitoring, (2) the pilot can detect system failure by observing airplane performance and motion, and (3) system authority and rate limits preclude structural damage in the presence of hardover or oscillatory failures.

Two of the triplex ACT Primary Computers command the rudder control surfaces through parallel force-summed secondary servos, similar to the elevator. Mathematical servo models are implemented in the triplex computers to provide fail-operational capability.
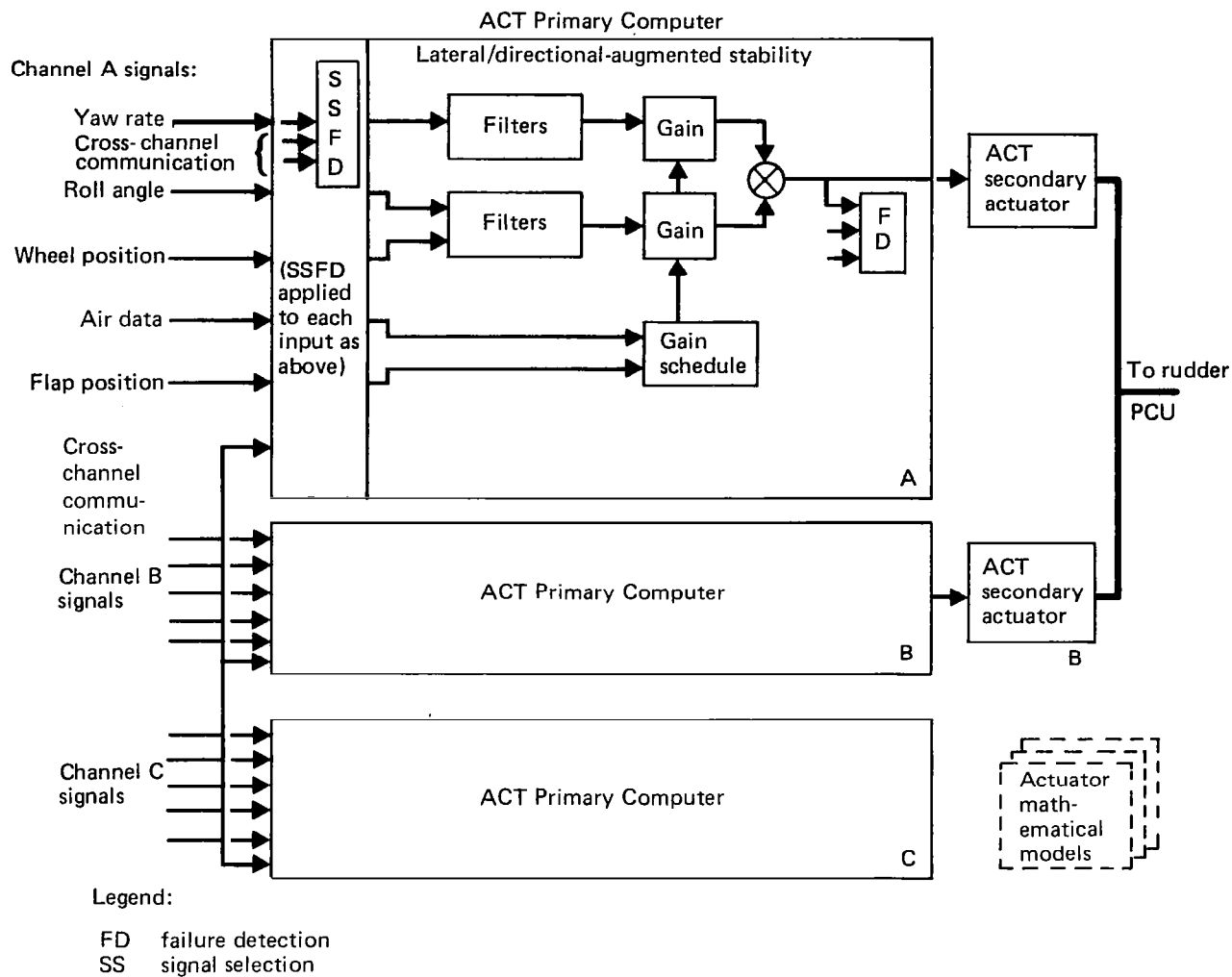
Figure 16. Lateral/Directional-Augmented Stability Block Diagram

ACT Primary Computer

Channel A signals:

Yaw rate
Cross-channel communication
Roll angle

Wheel position

Air data

Flap position

Cross-channel communication

Channel B signals

Channel C signals

Lateral/directional-augmented stability

SSFD

(SSFD applied to each input as above)

Filters

Gain

Gain schedule

FD

ACT secondary actuator

To rudder PCU

ACT Primary Computer

ACT Primary Computer

Actuator mathematical models

Legend:

FD   failure detection
SS   signal selection

33

Wing-Load Alleviation

The wing-load alleviation (WLA) function, which includes maneuver-load control (MLC) and gust-load alleviation (GLA), is implemented in the triplex ACT Primary Computers. Figure 17 is a block diagram of WLA, showing sensors and control surfaces. The WLA function commands deflections of the inboard and outboard flaperons, the outboard aileron (both segments), and the elevator. Airplane center-of-gravity and wing normal acceleration signals, gain scheduled from air data signals out of the triplex digital air data computers, are used to command appropriate control surface deflections to achieve the desired maneuver-load distribution and gust-load reduction.

MLC controls wing-load distribution resulting from pilot-commanded maneuvers and reduces low-frequency gust loads. The principal MLC signal is center-of-gravity normal acceleration. To compensate for the pitching moment resulting from symmetric aileron deflection, an elevator command is sent to the Essential PAS Computers, where it is summed with other elevator commands.

The principal GLA signal is wing normal acceleration. GLA controls the high-frequency gust loads through appropriate commands to the outboard aileron (inboard and outboard segments).

WLA and pilot commands to the outboard segment of the outboard aileron are mechanically summed, producing an input command to the outboard aileron actuators. WLA commands to the inboard segment of the outboard aileron are electrically summed (in software) with flutter-mode control and pilot commands before being transmitted to the dual force-summed inboard segment actuators. The flaperons are used solely as WLA surfaces and are electrically signaled from triplex ACT Primary Computers.

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ACT Primary Computer

Channel A
signals:

Wing normal
acceleration

Cross-
channel
communication

Wing-load alleviation

$$\frac{s}{(s+5)\,(s/35+1)}$$

$$\frac{1}{T(V)s+1}$$

$$\frac{1}{s/10+1}$$

$$\frac{s}{(s+5)\,(s/20+1)}$$

S
S
F
D

KM

KE

F
D

F
D

Right and left
flaperon actuators

Right and left
outboard aileron
(inboard segment)
actuators

Right and left
outboard aileron
(outboard segment)
actuators

Elevator
command

Acceleration
at center of
gravity

(SSFD
applied to
each input
as above)

Gain schedule

Air data
signals

Cross-
channel
communication

Channel B
signals

ACT Primary Computer

B

Channel C
signals

ACT Primary Computer

C

Legend:

FD   failure detection
KE   elevator gain
KM   maneuver gain
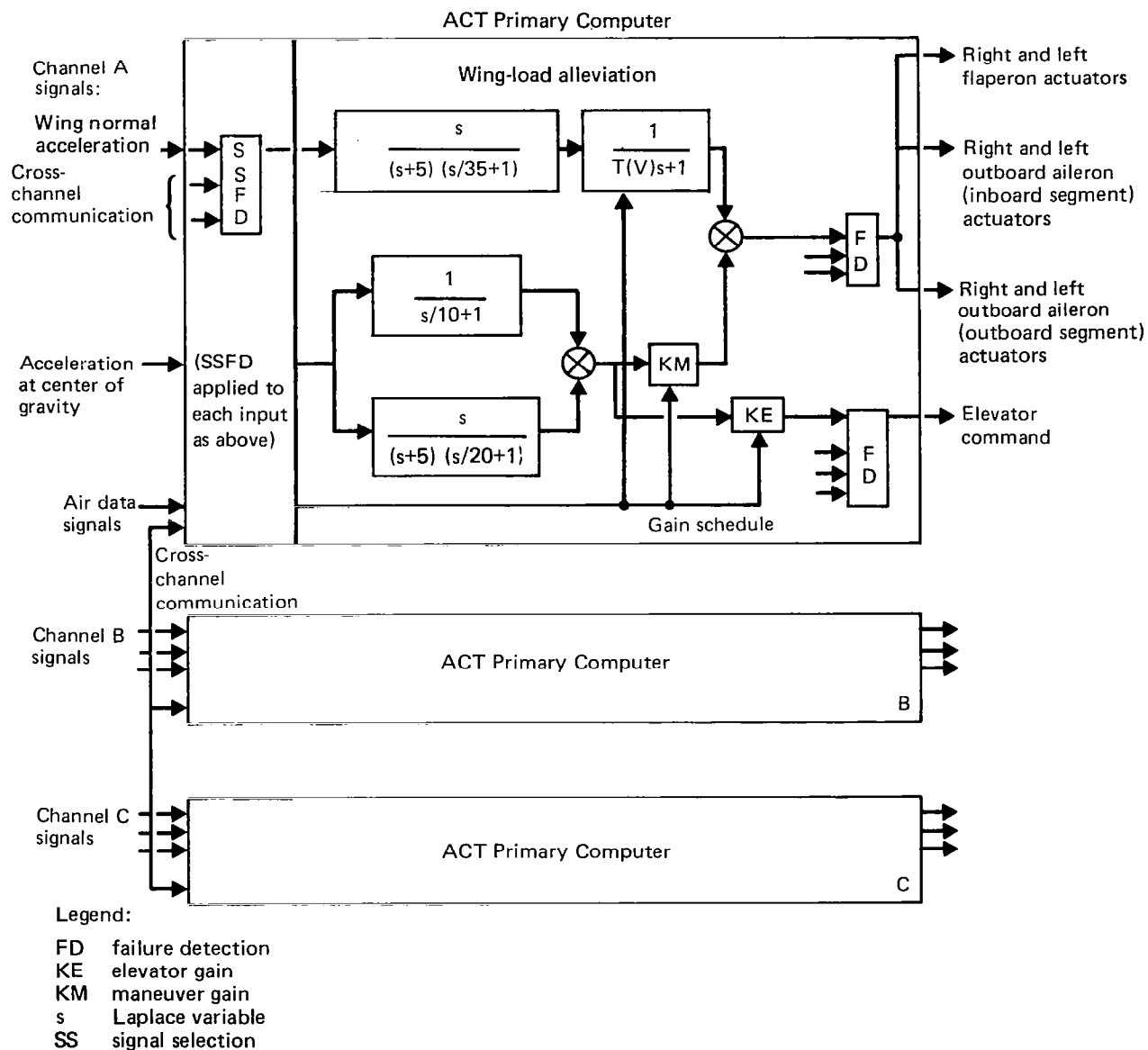s   Laplace variable
SS   signal selection

Figure 17. Wing-Load Alleviation Block Diagram

35

Flutter-Mode Control

The flutter-mode control (FMC) function suppresses wing flutter modes for airspeeds between dive and 1.2 times the dive speed. Figure 18 is a block diagram of the FMC function. FMC uses sensed outboard wing normal acceleration to develop a command for the inboard segment of the outboard aileron. Triple accelerometer outputs from the right and left wing are processed through the signal selection and failure detection algorithm to generate a signal for the control law computation and sensor monitors. Air data signals from the digital air data computer are used in the control law to produce commands sensitive to various airspeeds. The output of the FMC control law is summed with pilot commands and wing-load alleviation control law output to form the inboard segment of the outboard aileron deflection commands.
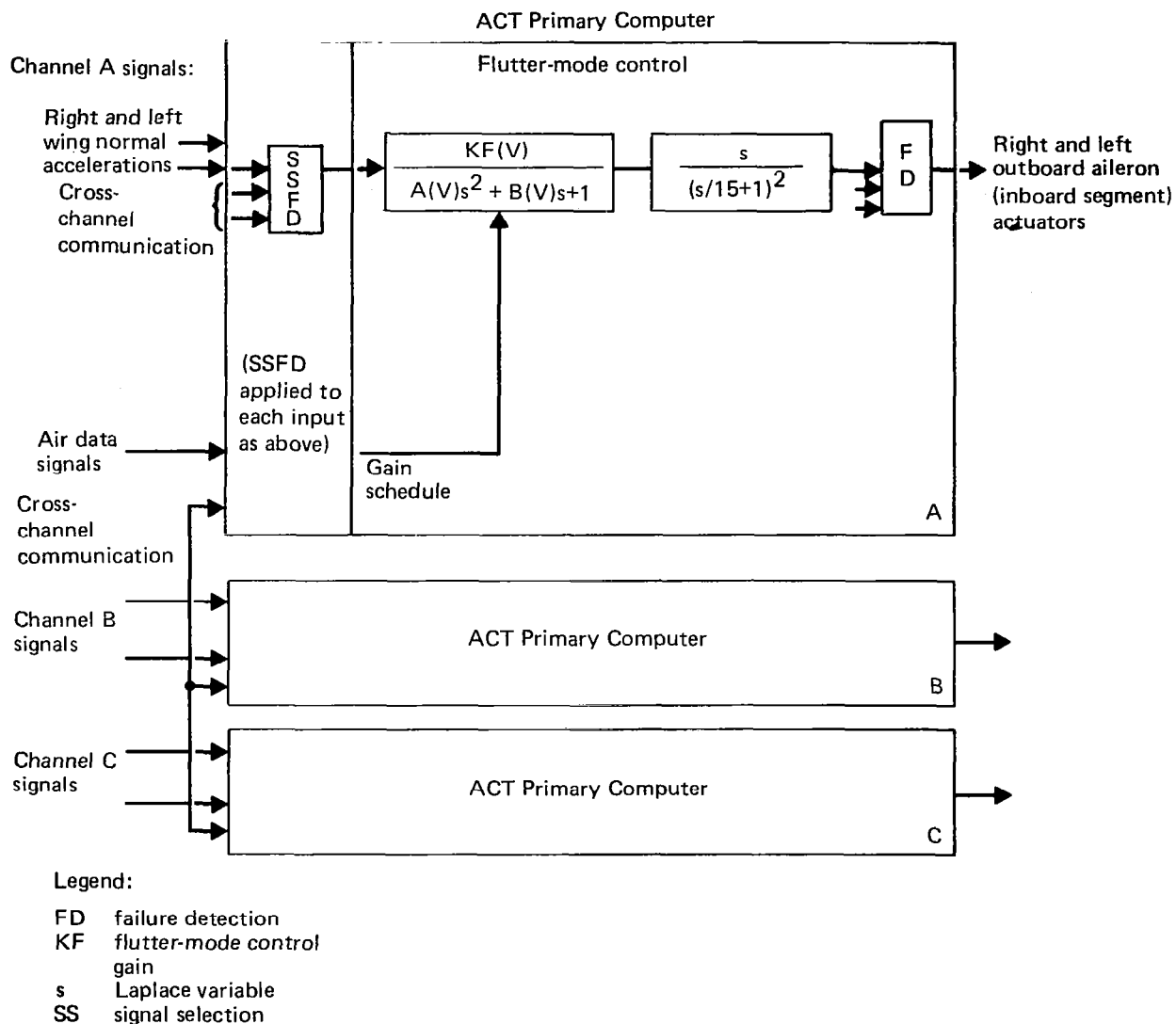
ACT Primary Computer

Channel A signals:

Right and left wing normal accelerations

Cross-channel communication

Flutter-mode control

$$\frac{KF(V)}{A(V)s^2 + B(V)s+1}$$

$$\frac{s}{(s/15+1)^2}$$

Right and left outboard aileron (inboard segment) actuators

(SSFD applied to each input as above)

Air data signals

Gain schedule

Cross-channel communication

Channel B signals

ACT Primary Computer

Channel C signals

ACT Primary Computer

Legend:

FD failure detection
KF flutter-mode control gain
s Laplace variable
SS signal selection

Figure 18. Flutter-Mode Control Block Diagram

REDUNDANCY MANAGEMENT

Redundancy Management in the ACT Primary Computers

Redundancy management is the process that enables continued operation of the ACT system in the presence of certain transient or permanent failures of the system. System elements are monitored for faults using a combination of hardware and software. Faults are primarily detected by cross-channel comparison, with inline monitoring supplementing cross-channel comparison to provide fault isolation. Critical systems will survive any single failure, except actuator jam, without affecting performance. The crucial system will survive two similar failures, including a jam. The crucial system can survive an actuator jam because both elevator servos and power control units are triplex and force voted. Following clearance of a transient fault, the system recovers to the redundancy level in effect before the failure. Following a failure that leaves only two success paths for a function, a subsequent disagreement in those paths will lead to shutdown of the function or reconfiguration to a degraded mode. Single-thread operation will be allowed only if it can be shown that a subsequent failure is not a threat to the safety of the airplane.

These redundancy management goals are achieved by system monitoring and reconfiguration and additional failure protection through design features such as physical and functional isolation in redundant channels, supplying electric power from redundant sources, and hydromechanical voting. System monitoring and reconfiguration is performed under the control of the ACT Primary Computers and the Essential PAS Computers on three separate planes: sensors, computers, and servoactuators. Figure 19 illustrates the redundancy management processes performed by the ACT Primary Computers.

Signal selection and failure detection (SSFD) protects against failures of the sensors, wiring, and input sections of the computer. Each computer uses SSFD to select a single value from each set of redundant sensors and uses failure detection and reconfiguration to isolate failed sensors. SSFD is performed primarily in software for those sensors whose output normally has a steady-state (dc) component (e.g., airspeed and angle of attack); the last "good" value is held whenever two of the three sensors fail. For those sensors with values that are normally zero, the selected value is set to zero when the sensors fail.

Failure detection is accomplished by comparing input signals in error detectors. These detectors have different thresholds and detection times for dynamic failures and for static errors. For signals that are not equalized, there is only a single detector, which is essentially a dynamic fault detector. Each detector uses a counter scheme to prevent nuisance trips and to provide oscillatory failure protection. Signal selection operates on those signals that have not exceeded thresholds. When a signal has been determined to be failed, sensors are reconfigured to exclude that signal from the selection process, but the fault detector continues to monitor all signals. The selection process selects the median signal when none of the signals has failed and averages the unfailed signals when only two good signals remain.
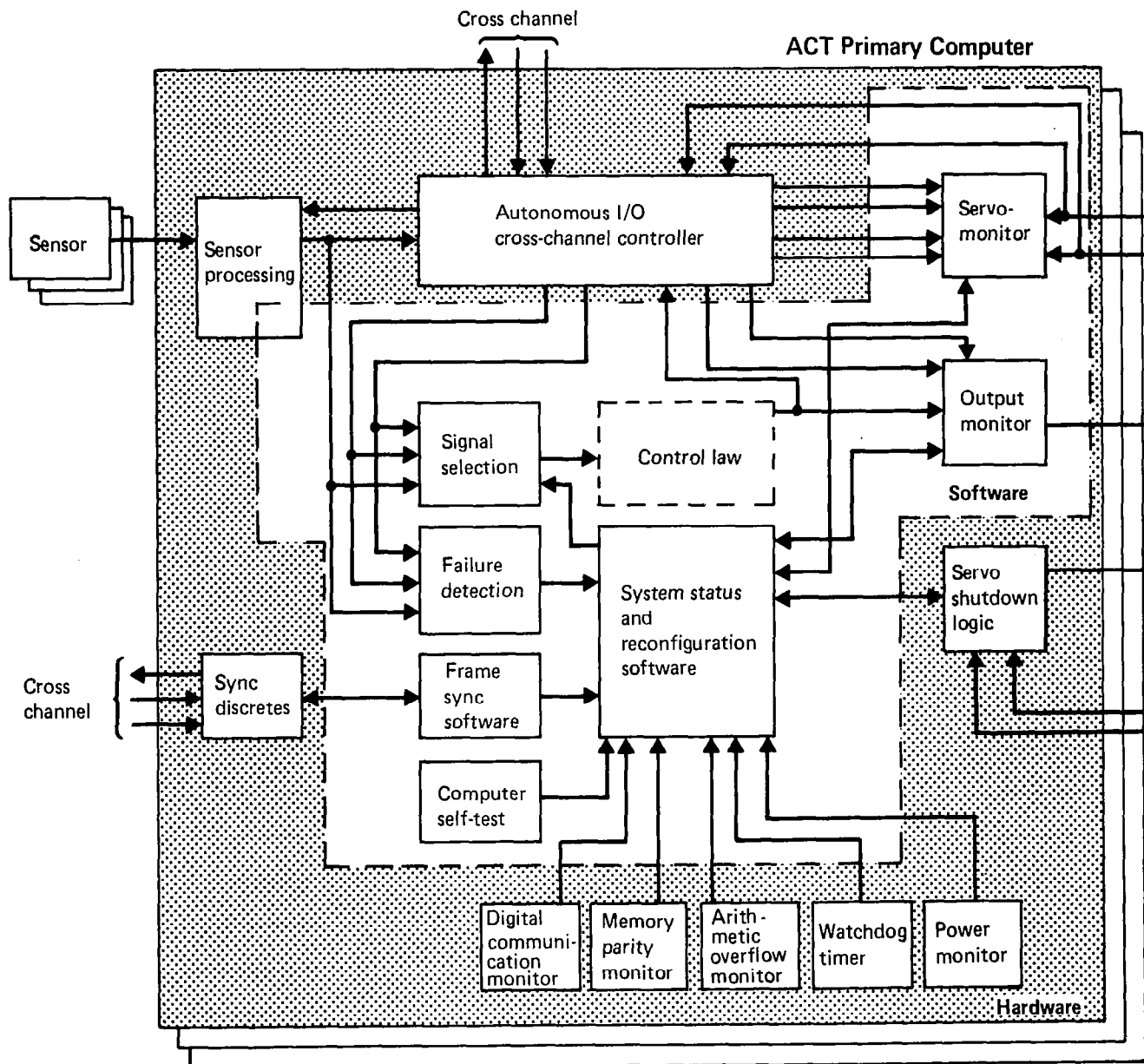
Figure 19. Redundancy Management Processes, ACT Primary Computer

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Redundancy Management in the Essential PAS Computers

Redundancy management in the Essential PAS Computers is portrayed in Figure 20. Sensor selection is slightly more complex in the quadruple Essential PAS Computers than in the triplex ACT Primary Computers. An active, online selection process is used for the four dedicated pitch-rate sensors; three signals are considered active and are fed directly into the selector. All four signals are monitored for failure, but the standby signal is not used unless one of the active signals fails.

The selection process becomes (1) median of active channels with no failures; (2) after the first failure, median of active channels with the standby channel replacing the failed channel; (3) after the second failure, average of unfailed channels; and (4) with three failures, a "best-value" selection. Best-value selection uses inline monitoring to select the remaining good signal, but because it does not provide 100% failure detection, it may not be possible to determine the good sensor. Loss of sensor data for the Essential PAS Computer can result in loss of pitch augmentation, which must be extremely improbable. Therefore, one of the signals is arbitrarily selected if inline monitoring does not provide enough information to determine which of the sensors has failed. Reliability analyses indicate that loss of three sensor signals in the Essential PAS System meets the extremely improbable criterion.

The Essential PAS Computers also select the Full PAS signal from the ACT Primary Computers to command the elevator. The SSFD algorithm used in this instance is altered to account for simultaneous failures, as redundancy management of the ACT Primary Computers masks the effect of sensor failures on the output. A single sensor failure will not affect the output, but a second similar failure can cause all three ACT Primary Computers to simultaneously shut down their outputs. The Essential PAS Computer cannot obtain sufficient information about the PAS command from the ACT Primary Computers by comparison monitoring alone to properly determine the status of that command. Discrete status bits from the ACT Primary Computer are used to augment the monitor information. If a signal fails a comparison, or a vote of the status bits indicates a signal has failed, that signal is no longer used by the selector. If two or more signals fail, the PAS command from the ACT Primary Computers is disregarded and the output from the Essential PAS control law computation is substituted.

For both ACT Primary and Essential PAS Computers, the sensors are continuously monitored. If a failed signal returns to within tolerance for a prescribed period of time and inline testing indicates it is good, the sensor is considered recovered and once again becomes active.
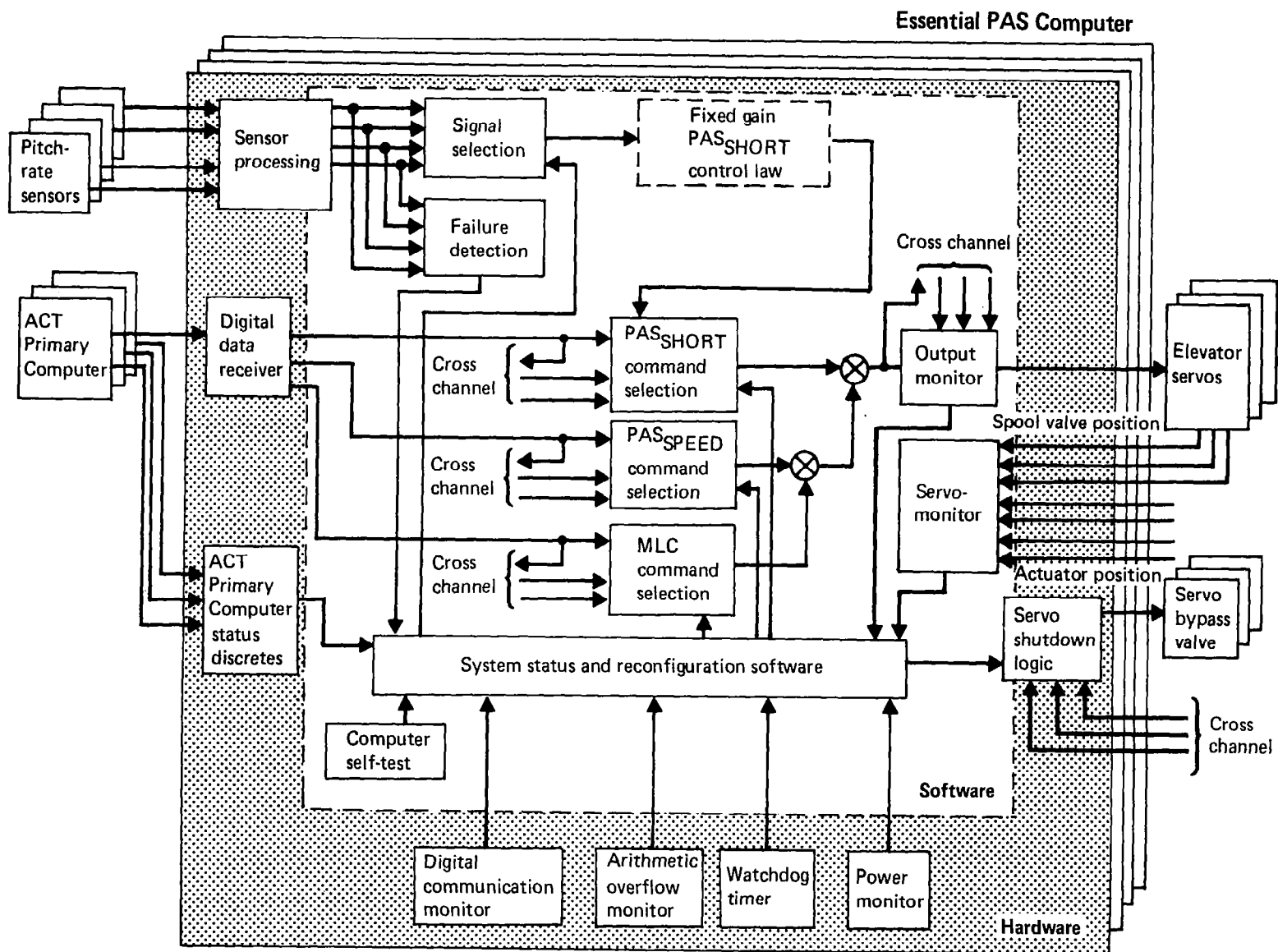
Figure 20. Redundancy Management Processes, Essential Pitch-Augmented Stability Computers

System Test and Maintenance

Successful commercial operation of an active control transport will depend upon a comprehensive system self-test capability. This testing falls into two broad categories: preflight (both electronic and mechanical) and in-flight. Figure 21 is an overview of the test and maintenance activity and the location where that activity occurs.

One objective of the IAAC Project was to design an active control system so structured that the ACT computers do the system self-test. The self-test must recognize single or multiple ACT function loss and its impact on airplane operability. The electronic preflight test (initiated by the crew) occurs at the gate, simultaneously in the ACT Primary Computers and the Essential PAS Computers, and requires less than 30 sec, compared to a normal departure preparation time of approximately 10 min. The electronic preflight test tests computers, sensors, and interfaces among computers, sensors, and actuators. If no faults are identified or if they are such that the airplane can continue, either with or without restriction, the airplane is cleared to depart. Otherwise, the airplane cannot be dispatched.

The mechanical part of the preflight test requires ground clearance and would normally be accomplished while the airplane is taxiing to the takeoff position; minimum taxi-out time for this type of airplane is about 4 min. It is estimated that the ACT mechanical preflight (checking servo response) requires about 30 sec and would accompany the normal control pullthrough (movement of the cockpit controls to verify proper control surface movement) that the crew accomplishes during taxi. The airplane is cleared for flight if the test is successfully passed.

System self-test during flight is a continuous monitoring activity. The ACT computers perform multiple control law and redundancy management calculations during flight and also monitor the system. The computer memory required for system test is estimated to be 8200 words in the ACT Primary Computers and 5500 words in the Essential PAS Computers. In-flight monitoring begins automatically with the no-weight-on-wheels condition following lift-off and verifies that computers, interfaces, sensors, and actuators are all functioning normally. In the absence of a fault, flight continues in a normal manner. The identification of a fault can result in one of three conditions. Faults that do not affect continued safe operation of the airplane are simply flagged for subsequent maintenance action and the airplane proceeds without restriction. Other faults will require introducing a restricted flight envelope within which the airplane can continue the mission. The third result from a fault identification could be diversion to the nearest available field (not shown on the figure).

For faults that affect operation (e.g., dispatchability, continued normal operation, introduction of a restricted flight envelope, or the need to divert), the system determines the status of the ACT function or functions affected by the fault and displays that status advisory messages provided by the ACT Maintenance and Display Computer. Certain fault categories, although requiring no specific change in the operation of the airplane
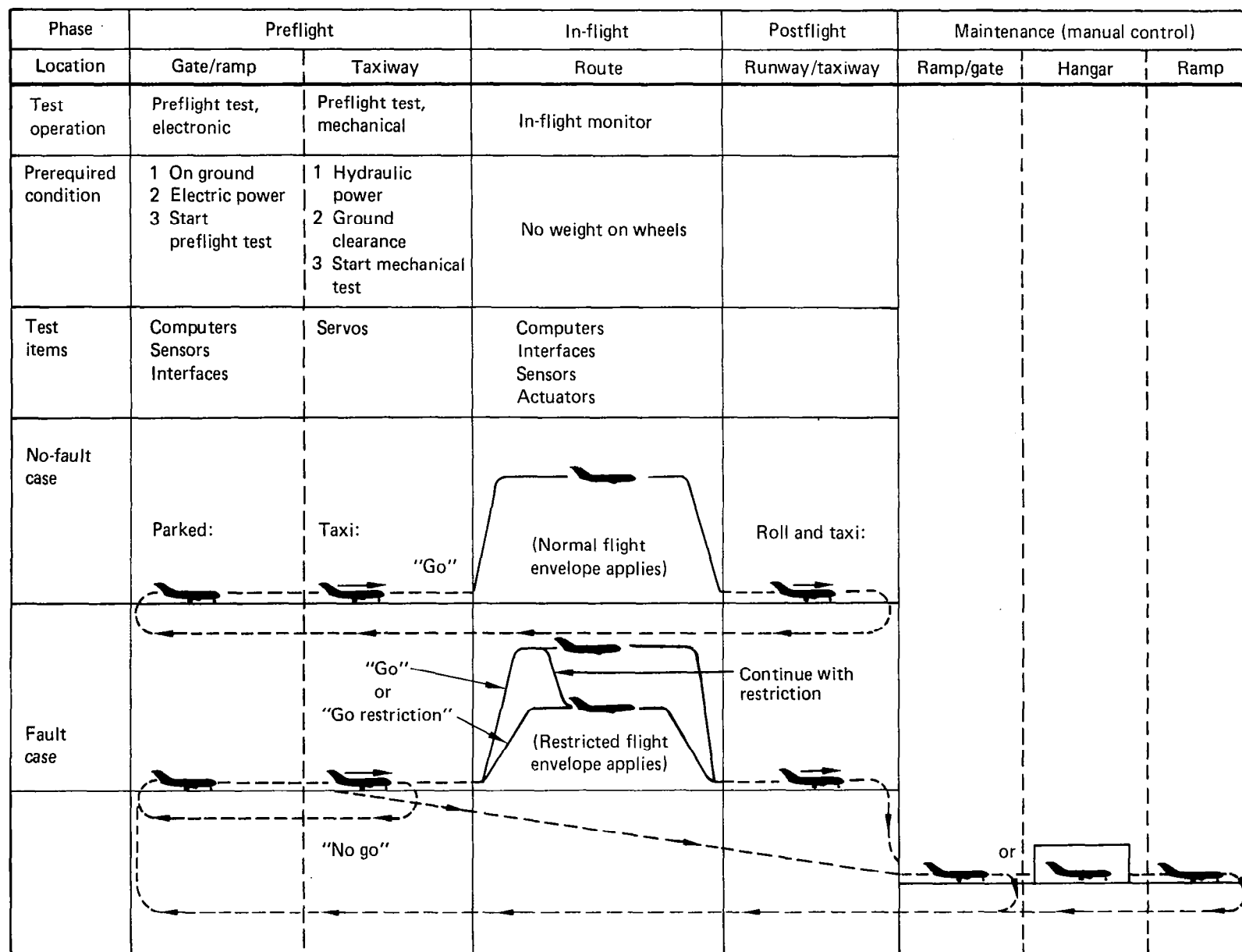
Phase	Preflight		In-flight	Postflight	Maintenance (manual control)		
Location	Gate/ramp	Taxiway	Route	Runway/taxiway	Ramp/gate	Hangar	Ramp
Test operation	Preflight test, electronic	Preflight test, mechanical	In-flight monitor				
Prerequired condition	1 On ground 2 Electric power 3 Start preflight test	1 Hydraulic power 2 Ground clearance 3 Start mechanical test	No weight on wheels				
Test items	Computers Sensors Interfaces	Servos	Computers Interfaces Sensors Actuators				
No-fault case	Parked:	Taxi: "Go"	(Normal flight envelope applies)	Roll and taxi:			
Fault case		"Go" or "Go restriction" "No go"	Continue with restriction (Restricted flight envelope applies)			or	

Figure 21. Test and Maintenance Overview

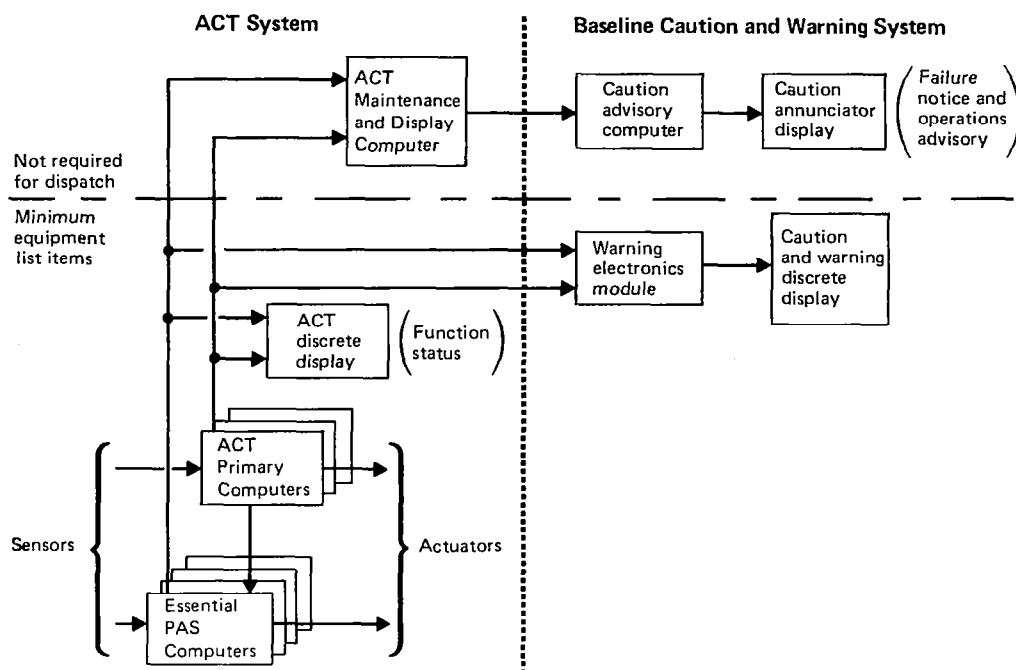## ACT Maintenance and Display Computer

The ACT control laws reside in either the triplex ACT Primary Computers or the quadruple Essential PAS Computers. This use of two separate sets of control computers necessitates a separate maintenance and display computer unit to coordinate communication of start of test, annunciation of significant failures, selection and transmission of appropriate operations advisory messages, and retention of fault information for maintenance use. The ACT Maintenance and Display Computer meets these requirements. As shown in Figure 22(a), it is not necessary for dispatch.

In its normal mode of operation, the ACT Maintenance and Display Computer accepts fault information from the ACT Primary Computers and the Essential PAS Computers. This information is processed in the ACT Maintenance and Display Computer to determine function status and the resulting advisory message(s), if required. This processing, combined with the basic caution and warning system of the airplane, presents the crew with essential fault information and any necessary operational changes. Thus, when the ACT Maintenance and Display Computer is active, the pilots do not need to refer to an operations manual to determine their appropriate response to an ACT system failure.

Figure 22(b) summarizes the various crew communication provisions associated with the ACT system. In the primary operating mode, the caution annunciator display will report all system information essential to the flight crew. This information includes identification of failed line replaceable units (if they are required for dispatch) and any change in flight plan made necessary by system failures. Fail-operative communication from the ACT system to the flight crew is achieved through the baseline caution and warning system plus dedicated discrete indicators showing the status of all ACT functions.

In the backup mode, following the loss of the ACT Maintenance and Display Computer or the caution annunciator panel, the dedicated discrete status indicators are the principal means of communication to the crew. Flight manual data are provided to interpret those indicators in terms of required operations changes; e.g., dispatch or not, continue without restriction, etc.

In normal operation, system failures are followed by automatic reconfiguration or automatic function disconnect. Manual control will be provided only for initiation of preflight test and emergency disconnect.

ACT System | **Baseline Caution and Warning System**

ACT Maintenance and Display *Computer*

Caution advisory computer → Caution annunciator display   (Failure notice and operations advisory)

Not required for dispatch

Minimum equipment list items

Warning electronics *module* → Caution and warning discrete display

ACT discrete display   (Function status)

ACT Primary Computers

Sensors

Actuators

Essential PAS Computers

(a) ACT Displays

	Function	Indicators①		Switches (momentary contact, illuminated)	Remarks
Manual	Start preflight, electronic	———→		Electronic (Test)	ⒶSwitch illuminated during test, off at end
	Start preflight, mechanical	———→		(Test) Mechanical	See Ⓐ above
Active control	PAS SHORT		④ Red | Divert		Requires immediate diversion; function is never disconnected
	PAS SPEED	Marg | Amber ② | Inop | Amber		(Off) ③ (On)	Ⓑ Switch pushed to disable function remains illuminated as long as function is disconnected
	LAS	Marg | Amber | Inop | Amber ④		(Off) (On)	See Ⓑ above
	WLA	Marg | White | Inop | Amber		(Off) (On)	See Ⓑ above
	FMC	Inop | Amber		(Off) (On)	See Ⓑ above ©"Marg" is not significant
	Stall warning and AAL	Inop | Amber		(Off) (On)	See Ⓑ above See© above
	Failure information display	Master indicator: Warning Red / Caution Amber. Each end of glare shield	(Alphanumeric color CRT; 11 lines, 16 characters/line) Cancel / BRT \ Recall	Caution annunciator display 1. Pilot's main panel 2. Flight engineer's panel	Annunciators and master indicators are parts of baseline caution and warning system. Annunciator will display: (1) Failed dispatch-required LRU (2) Operations advisory messages

Notes:
① If flaperons are required, flaperon position indication must be provided.
② Marg = one failure away from function loss. Inop = function inoperative, auto or manual disconnect.
③ Disconnect switches (five) allow manual disconnect of individual functions. "On" switches enable reconnecting functions.
④ Signaled by PAS SHORT lost or combination of PAS SPEED, LAS, and WLA lost.

(b) ACT Cockpit Displays Requirement

Figure 22. ACT Cockpit Displays

Software Reliability

The probability of failure of the ACT system crucial function during a 1-hr flight must not exceed 1×10^{-9}. There is no generally accepted method to prove software reliability consistent with this requirement. Moreover, it would appear that it is not possible to define a study that could convincingly indicate that this order of reliability is attainable.

On the other hand, very high levels of reliability for real-time software have been demonstrated in command and control systems for space missions and operations. (One example is the system used in the Lunar Orbiter missions in 1966 and 1967.) High reliability in such systems results from a carefully conceived approach and plan that is implemented in a disciplined manner. Figure 23 shows the essential elements of this process, of which exhaustive testing is one of the most important.

The software design process indicated by the elements in Figure 23 may be long and involved, and some parts of the process become "iteration loops" as testing discloses shortcomings in the design. However, extensive experience in engineering real-time digital control systems (spacecraft and airplanes) has shown that this process is not only essential but also effective in producing highly reliable real-time software.
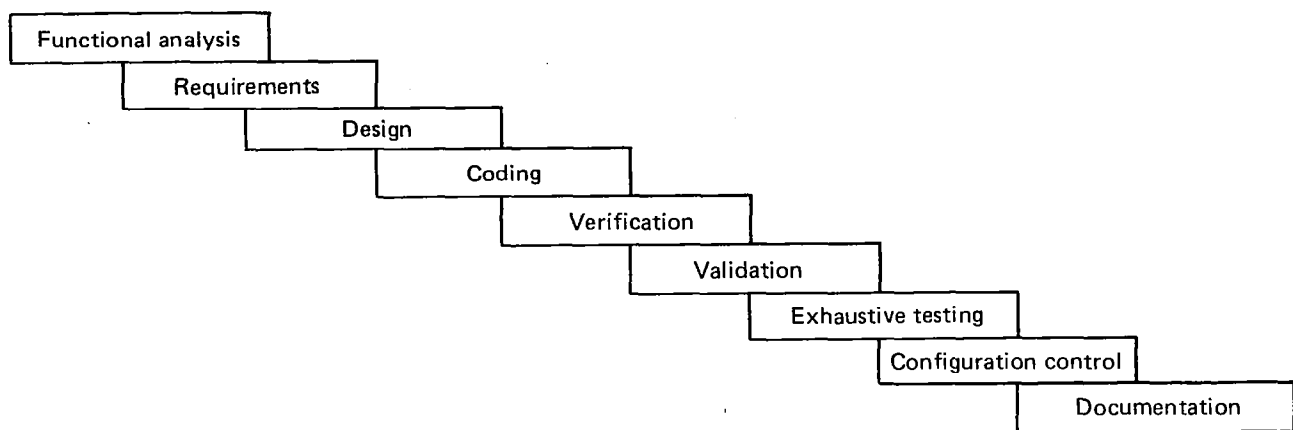
Figure 23. *Elements of Systematic Software Development*

ACT SYSTEM COST-OF-OWNERSHIP ANALYSIS

Calculation of ACT system cost of ownership contributes to an objective judgment of the various approaches to ACT system implementation. Present dollar values per flight hour are calculated for such economic parameters as fuel savings, maintenance cost, spares inventory cost, and system purchase cost. The analysis results are summarized in Table 3.

The results of the cost-of-ownership analysis are displayed as the return on incremental investment relative to the Conventional Baseline Configuration (ref 9).

Except for flaperons, the ACT systems are those previously discussed and include PAS, LAS, WLA, FMC, and AAL. The cost-of-ownership analysis was based on airplane cost, weight, performance, and maintenance cost estimates for the Initial ACT Airplane (refs 2 and 3), which implemented these desired ACT functions but did not use wing flaperons.

The analysis is based on a 1985 service entry date and an inflation rate of 10% per year on all cost-of-ownership parameters except fuel. Fuel cost was assumed to inflate at 15% per year and was $0.555/ℓ ($2.10/gal) in 1985 dollars. The principal assumptions in the analysis are that the airplane is being operated in a 30-aircraft fleet over an 863-km (466-nmi) average trip. The duration of this average trip is 1.25 flight hours. The incremental price of the ACT airplane is based on a 300-airplane production run, and it was assumed that the minimum attractive return on investment to the airline is 15%. All costs are in 1978 dollars unless otherwise stated. The Segregated System shows the highest incremental aircraft price because of the 21 computers used in that system, as compared with 4 larger computers in the Integrated System. The Selected System is significantly less expensive than the Segregated System but higher than the Integrated because of four additional small computers (Essential PAS Computers) and three additional dedicated pitch-rate sensors. Implementation of the Selected System with pitch fly by wire was examined briefly and showed the lowest incremental cost, largely due to the reduction in parts count resulting from deletion of the mechanical control system.

The incremental test equipment cost is based on the assumption that the airline would already possess basic digital test equipment for the rest of the digital electronic suite. The cost increment is thus based on additional equipment unique to the ACT system. The maintenance cost per flight hour is calculated based on past experience and recent predictions at the significant line replaceable unit level. The Integrated System displayed the highest incremental delay and flight cancellation cost ($0.54 per flight hour) because a single flight control computer or the IRS failure prevented dispatch of the airplane.

Considering the cost and performance parameters described previously as nominal, a sensitivity analysis was performed to determine the effect of variations in these parameters. The results of this analysis are shown in Figure 24. The line labeled "fuel saved or fuel cost" simply reflects the fact that in this sensitivity analysis it does not matter whether the fuel savings increase by 50% or the fuel cost increases by 50%, the effect was the same on the return on incremental investment. The equipment first-cost effect was much as would be expected. The result was much less sensitive to maintenance cost than had been originally anticipated and is very encouraging.

These return on incremental investment analyses show the ACT system and airplane to be a highly attractive investment at the expected fuel price inflation rates. The payback period for all systems is desirably short, and the return on incremental investment to the airline exceeded the 15% minimum attractive rate mentioned above.

Table 3. Cost-of-Ownership Results of Various ACT Systems

Parameter incremented	ACT technology base			
	Integrated	Segregated	Selected	Selected, pitch FBW
Aircraft purchase cost per aircraft	$274 000	$390 200	$297 100	$207 000
Maintenance manual cost per 30-airplane fleet	$21 000	$31 400	$26 100	$26 100
Test equipment cost per 30-airplane fleet	$22 500	$44 900	$33 600	$33 600
Spare inventory initial cost per 30-airplane fleet	$250 000	$356 000	$271 100	$271 100
Maintenance cost per aircraft flight hour	$4.18	$4.91	$4.22	$3.98
Departure delay and cancellation cost per aircraft flight hour	$0.54	$0.45	$0.19	$0.12
Change in system weight relative to Integrated System	0	+114 kg (+252 lb)	+14 kg (+30 lb)	-157 kg (-345 lb)
Fuel saving per flight hour at 863 km (466 nmi)	160 kg (352 lb)	146 kg (322 lb)	160 kg (352 lb)	172 kg (379 lb)
Payback period in years	2.83	4.14	2.98	2.02
Return on incremental investment to airline*	25.1%	22.1%	24.6%	27.6%

*Assumes 1985 introduction with fuel cost of $0.555/ℓ ($2.10/gal) and that fuel cost inflates at 15% per year against a general inflation rate of 10% per year.
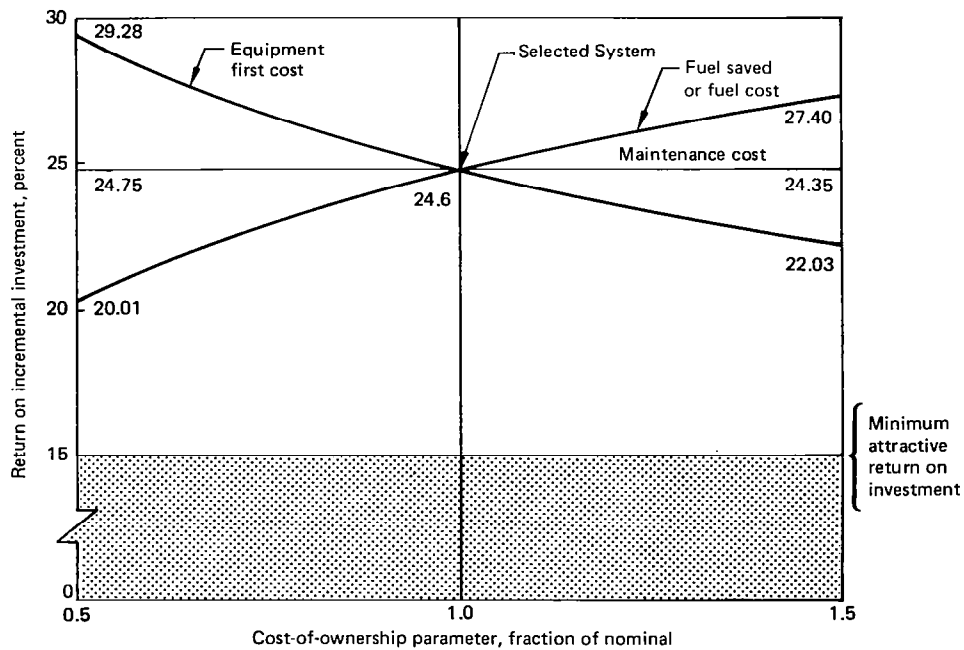

Figure 24. Effect of Changes in Cost Parameters on Return on Incremental Investment

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ADVANCED TECHNOLOGY ACT CONTROL SYSTEM DEFINITION

ADVANCED SYSTEM TRADE STUDIES

The overall objective of the Advanced Technology ACT Control System Definition Task was to define advanced ACT control systems for future commercial transports. The work consisted of two tasks: Advanced System Trade Studies and Implementation Alternatives. The classical approach of synthesizing one control loop at a time is not well suited to deal directly and efficiently with coupled multiloop systems or to take advantage of favorable interactions between the control loops. The objectives of the Advanced System Trade Studies were to develop control law analysis and synthesis methods suitable for a coupled multiloop system and to demonstrate the potential benefits of these methods by evaluating closed-loop performance of the resulting control laws. The methods used were based on modern optimal control and estimation theory. Control laws were synthesized for GLA, FMC, and rigid body (quasi-static aeroelastic) PAS and command-augmentation control laws.

GLA and FMC control law performance was evaluated based on indicated wing load (approximate expressions of the load contained in the mathematical model) and control surface activity, both in response to continuous random vertical turbulence and in response to discrete vertical gust. PAS control laws were evaluated based on pitch rate and load factor response to elevator commands.

Because of the complexity of the ACT control task and the dynamic characteristics of a typical flexible transport airplane, the ACT control law synthesis necessitates solving a coupled multiloop control problem. The design was accomplished using a set of experimental computer programs, based on time-domain modern control theory, suitable for the analysis and synthesis of multivariable controllers. Key elements are a state-space representation of the dynamic system, modal analysis, and optimal control and observer synthesis. The design process begins with model generation, then proceeds to the open-loop analysis, controller design, linear closed-loop analysis, and finally nonlinear closed-loop simulation. If necessary, the controller design process is repeated until satisfactory performance is achieved.

Control law synthesis and analysis require dynamic models of the flexible airplane, the actuation system, and wind disturbances, as well as measurement equations for structural displacements, velocities, accelerations, bending, torsion, and shear. These models are connected to perform open-loop analysis, control law synthesis, and, when combined with a control law, closed-loop performance evaluation. The airplane is represented at each flight condition by a set of constant coefficient, linear second-order differential equations with first-order lag terms. Figure 25 is a block diagram of a flexible airplane model. The individual blocks may represent nonlinear relationships.

The unsteady aerodynamic forces are modeled by an approximate transformation from frequency to time domain with a least-square fit of a second-order polynomial in the Laplace variable s. The result is steady and unsteady aerodynamic forces as functions of displacements and the corresponding first- and second-order time derivatives. The unsteady effects associated with gust inputs are approximated with Kussner lift-growth functions. Only linear actuator models are considered at this point in the analysis. Because of its simplicity, the Dryden turbulence model for vertical gusts was selected as representative of gust disturbances.
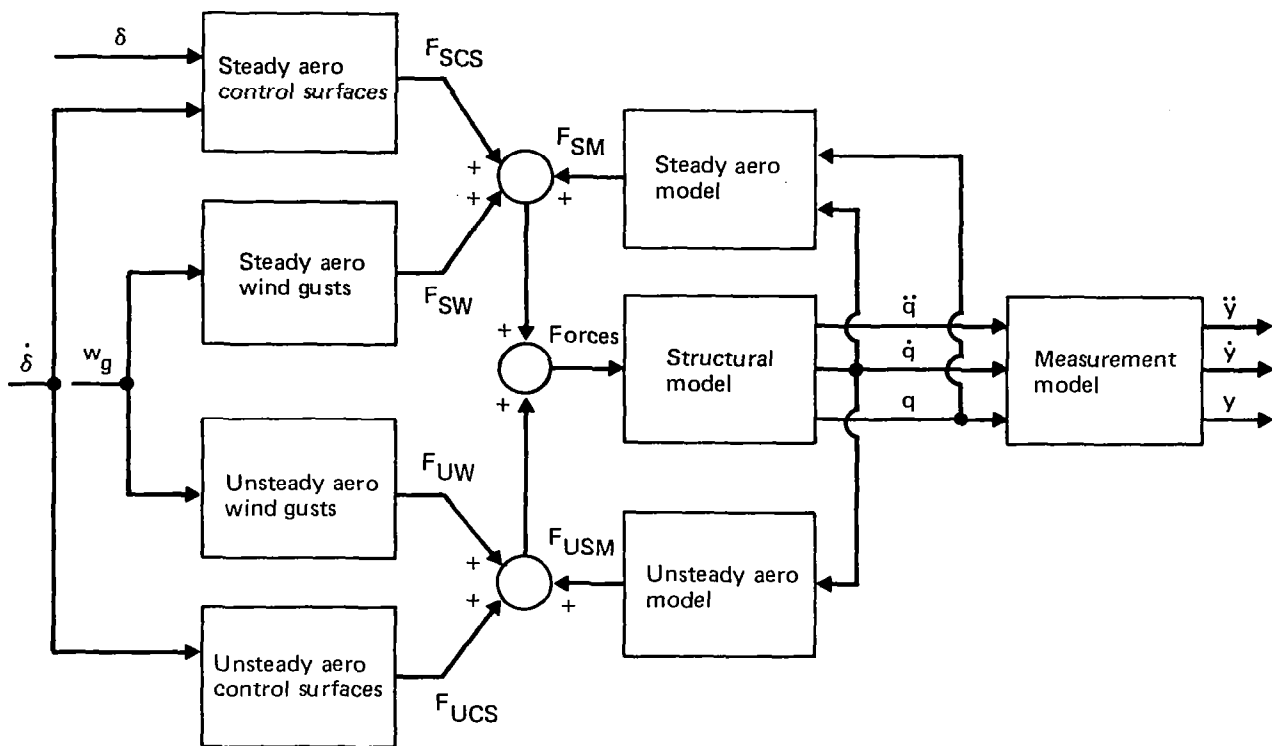
States of the system:

q   rigid- and flexible-mode deflections
$\dot{q}$ corresponding rates
$\bar{q}$ unsteady aerodynamic states associated with q
$\bar{\delta}$ steady aerodynamic states associated with δ
$\bar{w}_g$ unsteady gust states

Legend:

F_{SCS} steady aero control surface forces
F_{SM} steady aero forces
F_{SW} steady aero wind gust forces
F_{UCS} unsteady aero control surface forces
F_{USM} unsteady aero forces
F_{UW} unsteady aero wind gust forces
q   rigid- and flexible-mode deflections
w_g vertical gust velocities
y   measurement deflections
δ aerodynamic control surface deflections
(·)   differentiation with respect to time
(··)   double differentiation with respect to time

Figure 25. Model of the Flexible Airplane

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Final Integrated ACT Control Law

Constant gain control laws for suppression of the symmetric flutter mode and GLA were synthesized at eight separate flight conditions for the Initial ACT Airplane. These flight conditions corresponded to four speeds and two mass distributions. Four conditions were critical for GLA design and four were critical for FMC design. Six airplane control surfaces were considered: inboard and outboard elevators, inboard and outboard segments of the outboard aileron, complete outboard aileron, and inboard aileron. These surfaces were analyzed to determine their relative effectiveness in controlling the flutter mode and in producing load responses. The outboard aileron was best suited for flutter-mode control and the outboard aileron and elevator best suited for controlling wing loads. For this study, elevator and outboard ailerons were used as control surfaces.

Specific sensor selection criteria are described in Reference 6. The two most important criteria were mode observability and performance parameter observability. Twenty-seven accelerometer locations were evaluated. Three sensors were selected: one pitch-rate gyro at the airplane center of gravity to observe the short-period mode and two normal accelerometers (one in each wing) to observe the structural modes of the wing.

The best single location for an accelerometer was behind the outboard aileron hingeline near the wing tip. It provided high flutter-mode observability and high root-mean-square output and showed good correlation with inboard and outboard wing-bending moment indicators that had been embedded in the models of the airplane. The inboard wing-bending moment had been selected as the main gust-load parameter to be reduced through GLA control system design.

Control law design for GLA began with a full-state feedback system based on a cost function that included inboard bending moment, inboard torsion, outboard bending moment, outboard torsion, and aileron and elevator commands. Analysis of these control laws showed that the airplane short period was dominant in all loads and that the inboard torsion was most influenced by the flutter mode and the first engine strut mode. Elevator activity was dominated by the short-period mode, while aileron activity was dominated by the first structural mode. A Kalman state estimator was introduced that yielded a system with stability margin deficiencies at two of the flight conditions. This was corrected by making the Kalman filter more robust at the expense of slightly degraded performance. At this point, the 53rd-order Kalman filter was reduced to an 8th-order filter. The reduced-order filters for the four flight conditions were integrated, yielding one design that worked satisfactorily at all four gust-load flight conditions.

Development of the FMC control law designs paralleled the gust-load designs just discussed. The flutter mode of interest is caused primarily by coupling among wing vertical bending, wing torsion, and nacelle strut vertical bending, with a natural frequency of approximately 20 rad/s. The FMC goals were to achieve satisfactory structural damping at each of the flight conditions with moderate (50- and 75-deg/s root mean square) aileron rates for a gust intensity of 4.27-m/s (14-ft/s) root mean square. The final FMC control law required a 10th-order filter.

An integrated (GLA and FMC) 8th-order filter was produced by curve-fitting with selected poles and zeros from the gust-load and flutter-mode control designs. The final integrated design is shown in block diagram form in Figure 26. The control law uses parameter gain schedule as a function of speed.
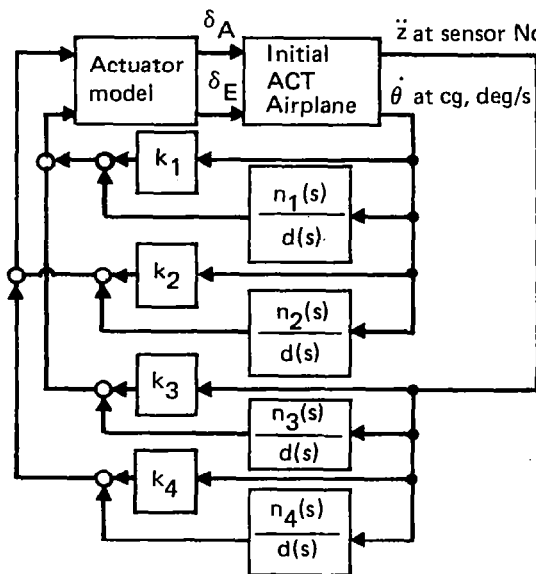
Legend:

δ_A — aileron deflection, deg
δ_E — elevator deflection, deg
$\ddot{z}$ — wing normal acceleration at sensor No. 11, m/s^2 (ft/s^2)
$\dot{\theta}$ — pitch rate, deg/s

$$n_1(s) = k_5(s^2 + 0.091s + 0.0027)(s + 0.35)(s^2 + a_1s + a_2)$$
$$(s^2 + a_3s + a_4)$$

$$n_2(s) = k_6(s + 0.33)(s + 0.33)(s + 0.018)(s^2 + b_1s + b_2)$$
$$(s + b_3)(s + b_4)(s + b_5)$$

$$n_3(s) = k_7(s + 5.2)(s + 0.315)(s^2 + 0.09s + 0.005)$$
$$(s^2 + c_1s + c_2)(s + c_3)$$

$$n_4(s) = k_8(s + 0.022)(s^2 + d_1s + d_2)(s^2 + d_3s + d_4)(s + d_5)$$
$$(s + d_6)$$

$$d(s) = (s^2 + 2.5s + 16.7)(s^2 + 0.48s + 0.06)$$
$$(s^2 + 0.055s + 8.5 \times 10^{-4})(s^2 + p_1s + p_2)$$

Parameter	Flight condition		Parameter	Flight condition	
	1, 2, 3, 4	5, 6, 7, 8		1, 2, 3, 4	5, 6, 7, 8
p_1	10.69	2.638	b_5	1.20	0.1217
p_2	30.69	376.4	c_1	16.93	10.61
a_1	13.64	4.127	c_2	89.3	674.2
a_2	50.98	5.789	c_3	-0.284	-1.515
a_3	2.053	-3.22	d_1	10.14	11.96
a_4	8.18	432.6	d_2	51.12	324.4
b_1	19.6	14.59	d_3	0.5335	-1.139
b_2	121.0	45.67	d_4	0.07673	1.765
b_3	-0.156	-126.0	d_5	5.38	0.2025
b_4	-1.24	-0.909	d_6	-0.0468	0.2025

Parameter	Flight condition			Parameter	Flight condition		
	1, 2	3, 4	5, 6, 7, 8		1, 2	3, 4	5, 6, 7, 8
k_1	38.8	38.8	3.78	k_5	36.5	36.5	0
k_2	7.37	8.03	0	k_6	-10.9	-11.9	0
k_3	-1.42×10^{-7} (-4.65×10^{-7})	-1.42×10^{-7} (-4.65×10^{-7})	0	k_7	-3.01×10^{-6} (-9.88×10^{-6})	-3.01×10^{-6} (-9.88×10^{-6})	
k_4	5.01×10^{-7} (1.64×10^{-6})	5.46×10^{-7} (1.79×10^{-6})	2.77×10^{-7} (9.08×10^{-7})	k_8	9.24×10^{-6} (3.03×10^{-5})	1.01×10^{-5} (3.30×10^{-5})	6.64×10^{-6} (2.18×10^{-5})

Note: Dimensions are in units of $m/s^2(ft/s^2)$ and deg/s

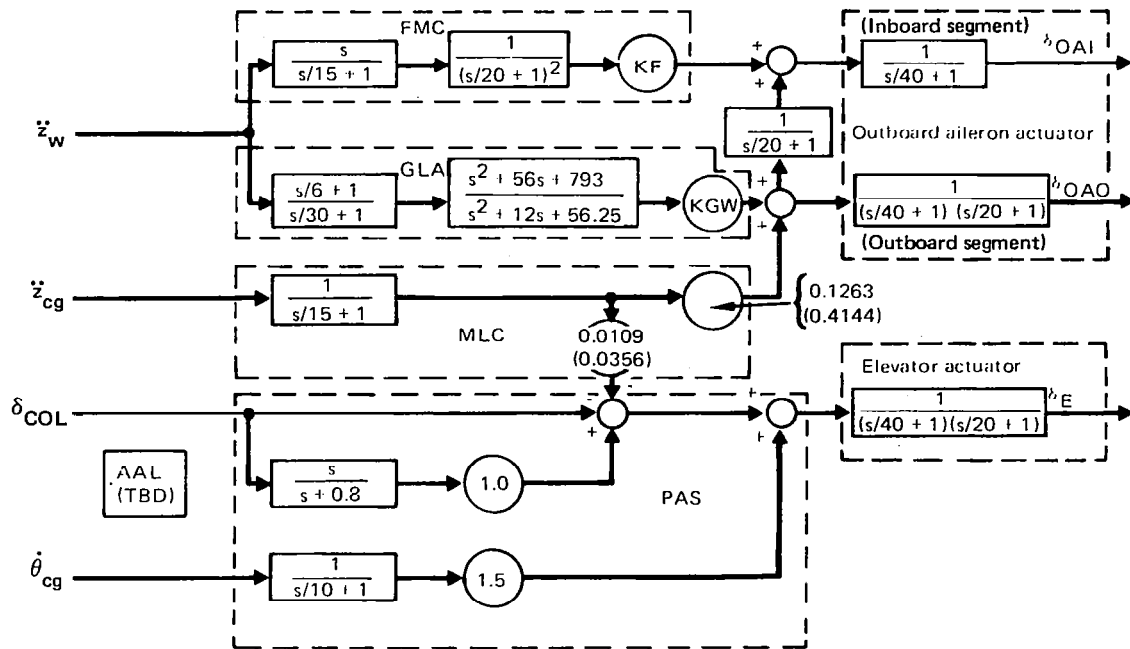*Figure 26. Block Diagram of Final Integrated Active Control Law Design*

Optimal and Classical Controller Comparison

Classical Controller Block Diagram—In support of the Initial ACT Airplane design activity, control laws were also synthesized for the eight flight conditions using classical techniques. A block diagram of the classical control law design is shown in Figure 27. Although these control laws are not the same ones assumed for the system simulation and reflected in Figures 14, 17, and 18, comparison of the performance of these classically developed control laws and the previously discussed optimal control and estimation-theory-based control laws can serve to highlight the results of these two approaches. The results were compared based on root-mean-square response to a von Karman gust and with a simulation using a discrete gust.

Several important distinctions should be noted with respect to the two designs. The optimal controller is an integrated multiloop filter that provides the GLA, FMC, and PAS functions. The classical approach relies on single-loop design techniques that result in separately designed filters for each function. In addition to GLA, FMC, and PAS, the classical design also addresses MLC.

These two designs use the outboard aileron in a slightly different manner. The optimal design uses the outboard aileron as a single surface, together with the elevator, for all control tasks. The classical design uses the inboard segment of the outboard aileron as a flutter-mode control surface, the total outboard aileron is used for load reduction, and the elevator is used for pitch augmentation.

Both designs use two types of sensors: a pitch-rate gyro at the airplane center of gravity and the wing-mounted accelerometer. The classical design uses a wing-mounted accelerometer somewhat inboard of that of the optimal design.

(Inboard segment)

FMC

$\dfrac{s}{s/15 + 1}$ $\dfrac{1}{(s/20 + 1)^2}$ KF $\dfrac{1}{s/40 + 1}$ δ_{OAI}

$\ddot{z}_w$

$\dfrac{1}{s/20 + 1}$ Outboard aileron actuator

GLA $\dfrac{s/6 + 1}{s/30 + 1}$ $\dfrac{s^2 + 56s + 793}{s^2 + 12s + 56.25}$ KGW $\dfrac{1}{(s/40 + 1)(s/20 + 1)}$ δ_{OAO}

(Outboard segment)

$\ddot{z}_{cg}$ $\dfrac{1}{s/15 + 1}$

MLC 0.0109 (0.0356) 0.1263 (0.4144)

Elevator actuator

δ_{COL} $\dfrac{1}{(s/40 + 1)(s/20 + 1)}$ δ_E

AAL (TBD) $\dfrac{s}{s + 0.8}$ 1.0 PAS

$\dot{\theta}_{cg}$ $\dfrac{1}{s/10 + 1}$ 1.5

Legend:

KF   FMC gain
KGW   GLA gain
δ_{COL} control column deflection, deg
δ_E elevator deflection, deg
δ_{OAI} outboard aileron deflection, inboard segment, deg
δ_{OAO} outboard aileron deflection, outboard segment, deg
$\dot{\theta}_{cg}$ pitch rate, deg/s
$\ddot{z}_{cg}$ body normal acceleration at cg, m/s^2 (ft/s^2)
$\ddot{z}_w$ wing normal acceleration at sensor No. 11, m/s^2 (ft/s^2)

Parameter	Flight condition		
	2	4	6
KGW	0.00189 (0.006188)	0.00105 (0.003438)	0.0
KF	0.00349 (0.01146)	0.00349 (0.01146)	0.0125 (0.04097)

Figure 27. Block Diagram of Classical Control Law Design

Random Gust Response—Table 4 shows the response of both designs to a random gust for flight condition 2. The classical control law performance is shown in response to a von Karman wind model, and the optimal control law performance is shown in response to both a Dryden and a von Karman model. The optimal controller was designed specifically for the Dryden model; hence, its performance is slightly better with the Dryden model than with the von Karman spectrum.

Table 4(a) shows the optimal design to be very comparable, in terms of bending moment, to the classical design. The optimal design is significantly better in reducing torsion at the inboard station than the classical design.

The most significant differences between the optimal and the classical design are shown in Table 4(b). The aileron deflection and rate requirements of the optimal system are significantly smaller than those required by the classical system. This is in part due to the approximately 25% greater root-mean-square (rms) elevator deflection and approximately 50% greater rms elevator rate of the optimal design. However, for both designs, the elevator activity is modest compared to the aileron activity.

Table 4. Random Gust Response Comparison, Flight Condition 2

(a) Incremental Load Reduction (Percent of Open Loop)

Design	Gust	Inboard bending moment, $\eta = 0.25$	Outboard bending moment, $\eta = 0.75$	Inboard torsion, $\eta = 0.25$
Optimal	Von Karman	71.2	65.6	91.2
	Dryden	68.5	61.9	87.4
Classical	Von Karman	70.4	61.9	101.0

η = fraction of semispan (2 y/b)

(b) Control Surface Activity

Design	Gust	Elevator deflection, deg	Elevator rate, deg/s	Outboard aileron deflection, deg	Outboard aileron rate, deg/s
Optimal	Von Karman	1.25	9.90	1.88	24.1
	Dryden	1.27	8.88	1.79	20.0
Classical	Von Karman	1.00	6.16	5.29[a] 4.53[b]	71.0[a] 33.6[b]

[a] Inboard segment of outboard aileron
[b] Outboard segment of outboard aileron
• Gust intensity = 8.5 m/s (28 ft/s)

Discrete Gust Response—To complete the comparison of these two system designs, their response to a 1-cos discrete gust was simulated. Table 5(a) shows the incremental load (measured as a percent of the open-loop peak load). The classical design reduces inboard bending moment slightly more effectively; the optimal design is slightly more effective in reducing outboard bending moment. With respect to bending moment, the two designs should be considered comparable. The classical design has a slightly higher torsion penalty as noted in the last column in Table 5(a).

The significantly lower aileron deflection and aileron rate requirements of the optimal design are shown in Table 5(b). These rates would have a significant impact on the hydraulic distribution system. The lower aileron deflection and rate requirements of the optimal design are in part due to the greater use of the elevator, as also shown in the table.

Table 5. Discrete (1-cos) Gust Response Comparison, Flight Condition 2

(a) Incremental Load Reduction at Peak (Percent of Open Loop)

Design	Inboard bending moment, η = 0.25	Outboard bending moment, η = 0.75	Inboard torsion, η = 0.25
Optimal	90.2	67.0	107.0
Classical	85.4	70.3	116.0

(b) Control Surface Activity

Design	Elevator deflection, deg	Elevator rate, deg/s	Outboard aileron deflection, deg	Outboard aileron rate, deg/s
Optimal	8.29	58.7	10.6	106.0
Classical	5.30	35.1	21.9[a] 21.6[b]	175.0[a] 142.0[b]

[a] Inboard segment of outboard aileron
[b] Outboard segment of outboard aileron

● Gust intensity = 28.5 m/s (93.4 ft/s)

Optimal and Classical Pitch Augmentation Comparison

PAS Controller Structure Comparison—Data in this section are presented to illustrate that both classical synthesis and optimal synthesis techniques can be used to create PAS controllers with acceptable system performance.

The optimal control design procedure consists of two parts: full-state feedback design and state estimator design. Only the control problem; i.e., the full-state feedback design, has been addressed here. Figure 28(a) shows the optimal controller structure. Explicit model-following was used to produce column command responses virtually identical to those of an ideal model. An advantage of the optimal control method is that it allows separation of the control and estimation problems. Normally, the full-state feedback design cannot be implemented without constructing a state estimator. Experience with the GLA and FMC control law designs, as discussed in Section 12.0 of Reference 6, indicates that acceptable performance would be obtained when the control law is modified to include a state estimator.

The classical methods of controller synthesis were used to design the PAS implementation shown in Figure 28(b). A quasi-steady aeroelastic model of the airplane with the three basic degrees of freedom (u, w, and q) was used in the design work.

A principal objective in the PAS design effort was the desire to keep the configuration simple, using a minimum of feedback signals and gain changes, and yet have it produce augmented airplane stability and handling characteristics that were entirely acceptable over a broad range of operational flight conditions.
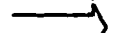
(a) Optimal Control

Switch states shown for
conditions 97 and 58.
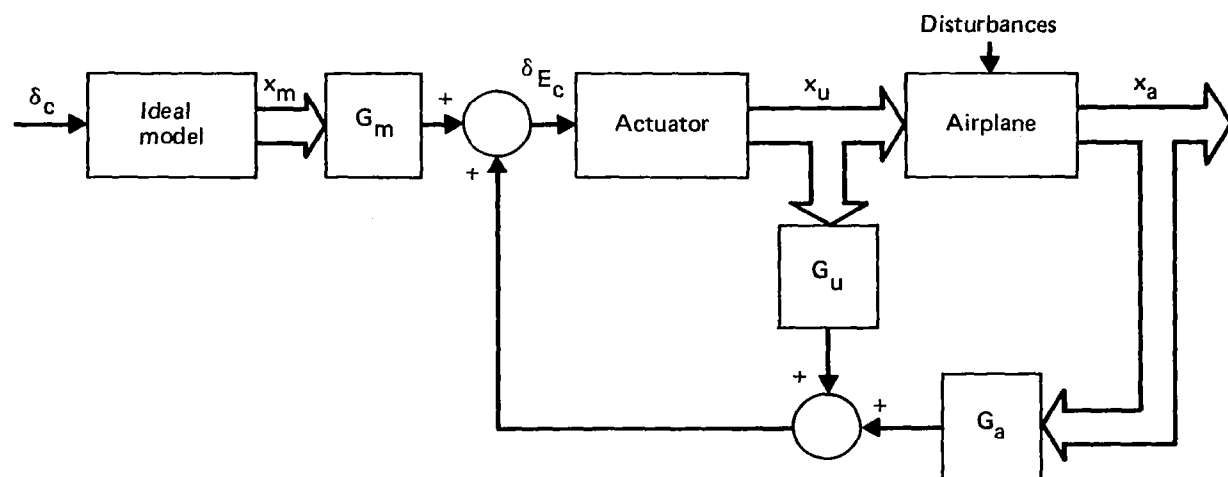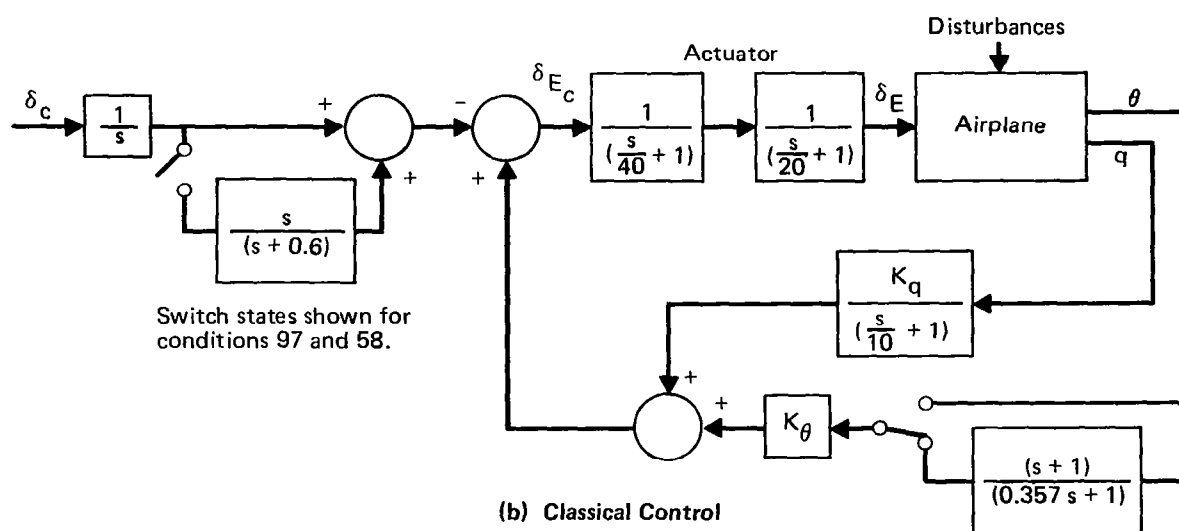
(b) Classical Control

Legend:

→	scalar signal
⇒	vector signal
u, α, q, θ	perturbation speed, angle of attack, pitch rate, attitude
x_a	airplane states (u, α, q, θ)
x_m	synthesized ideal model state variables $(u_m, \alpha_m, q_m, \theta_m)$
x_u	elevator actuator states
$G_m, G_u, G_a,$	gains
K_q, K_θ	
δ_c	elevator column
δ_E	elevator angle
δ_{E_c}	elevator command

Figure 28. Optimal and Classical Pitch-Augmented Stability Implementation

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Control Column Response—Responses of the optimal synthesis system, and the classical synthesis system, to step column inputs are compared in Figures 29, 30, and 31 for two flight conditions. These data show that both methods produce acceptable responses to column commands.

Flight condition 58 is a high-altitude, aft center-of-gravity condition. The Mach number is 0.65, altitude is 11 125m (36 500 ft), gross weight is 122 500 kg (270 000 lb), and the center of gravity is 0.46 mean aerodynamic chord. The classical system response can be characterized as a rapid rise with no overshoot, as shown in Figure 29. By comparison, the optimal system has a faster rise time with about a 50% overshoot, which produced a more rapid normal acceleration response. These two response characteristics are both estimated to yield satisfactory handling qualities. However, by changing the ideal model response, the optimal design could be made to match the classical system response.
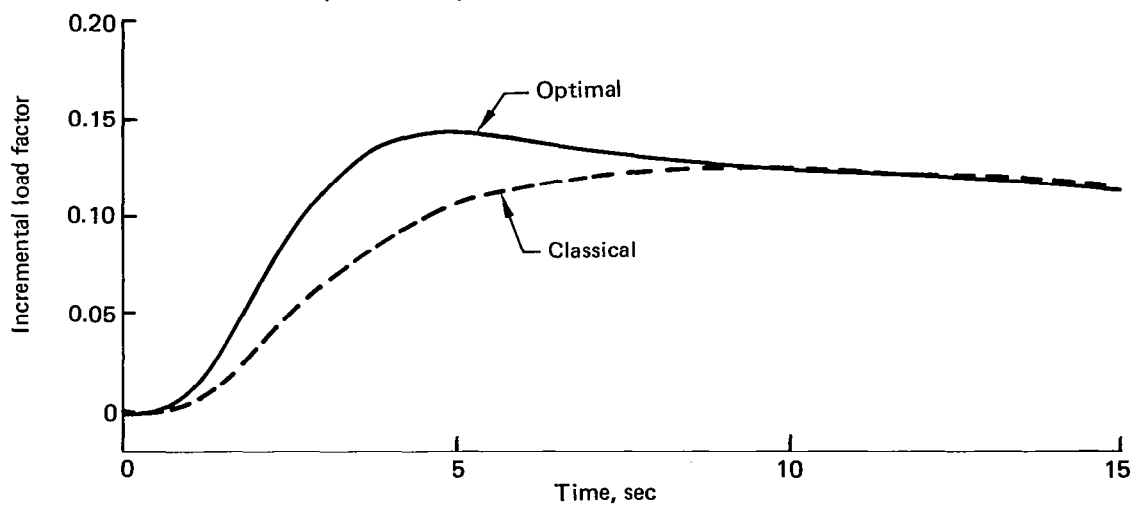
Flight condition 97 is a sea-level, flaps-down approach condition (1.3 times stall speed). The gross weight is 90 720 kg (200 000 lb) with the center of gravity of 0.46 mean aerodynamic chord. For this flight condition, the optimal system also has slightly faster response with small overshoot in pitch rate.

The elevator responses (fig. 31) of the optimal system and the classical system are similar for both flight conditions. This is to be expected because the character of the elevator response is determined largely by the stability of the vehicle and the desired response. Larger control deflections are required for the optimal system, because that system was designed for the Initial ACT Configuration, which is somewhat less stable than the aspect ratio 12 configuration (Wing Planform Study, refs 4 and 5), for which the classical system was designed.

An advantage of the optimal control law synthesis method is that it directly produced the feedback gains necessary to cause the augmented airplane to behave similarly to a desired response. The method allowed acceptable designs in response to command inputs as well as in response to turbulence.
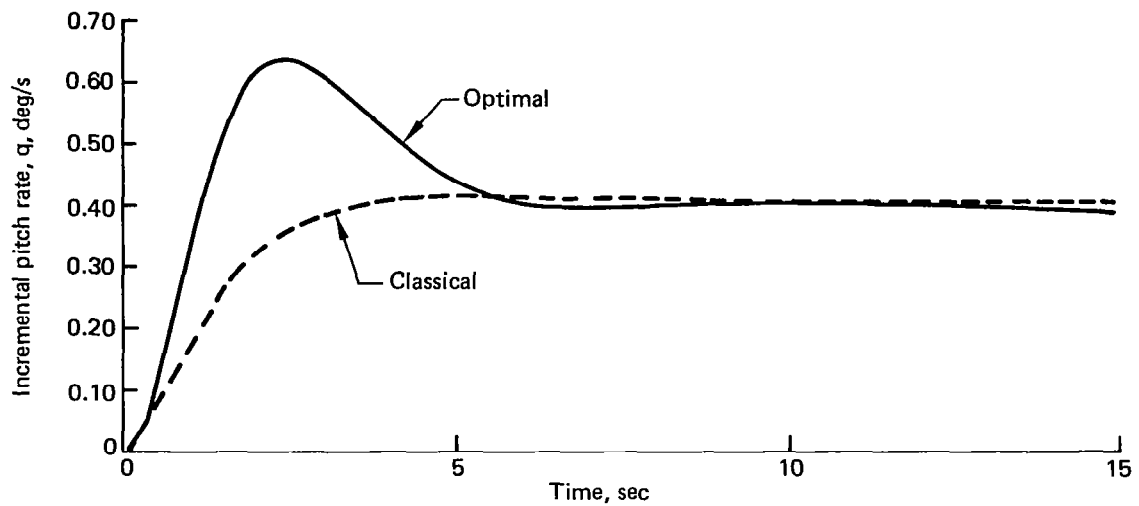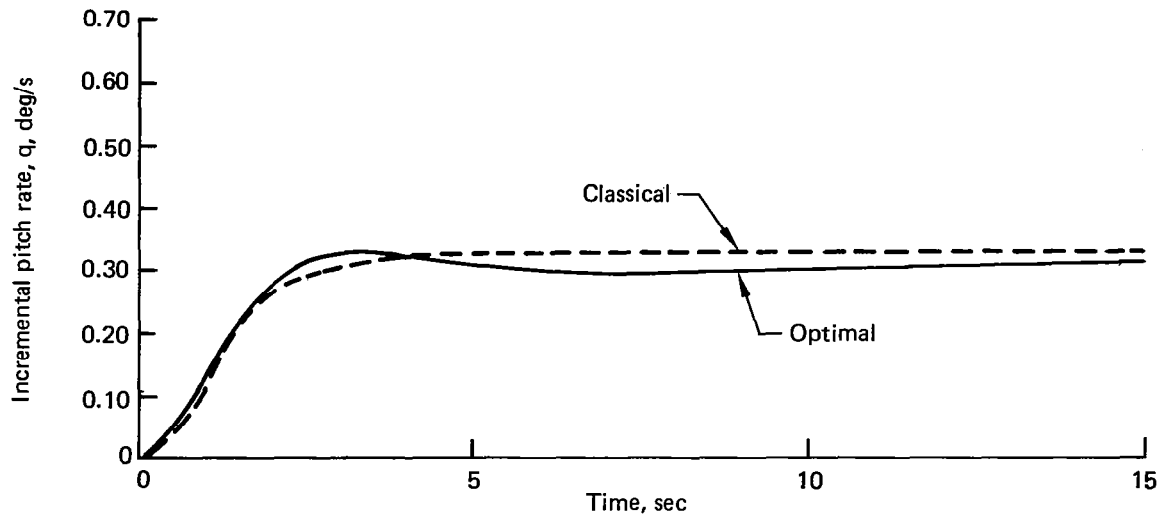
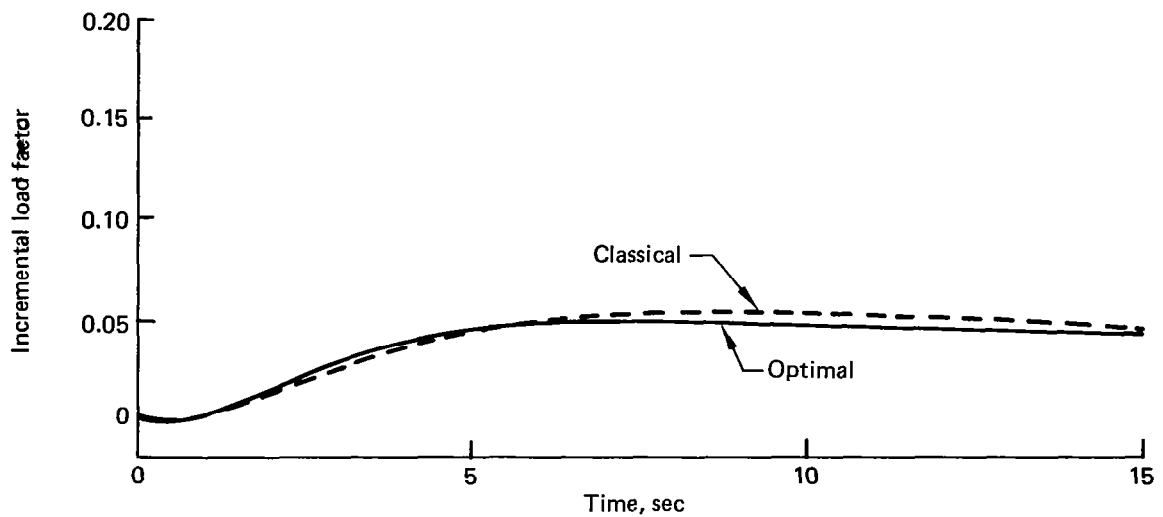(a) Pitch-Rate Response to Step Column Command

(b) Acceleration Response to Step Column Command

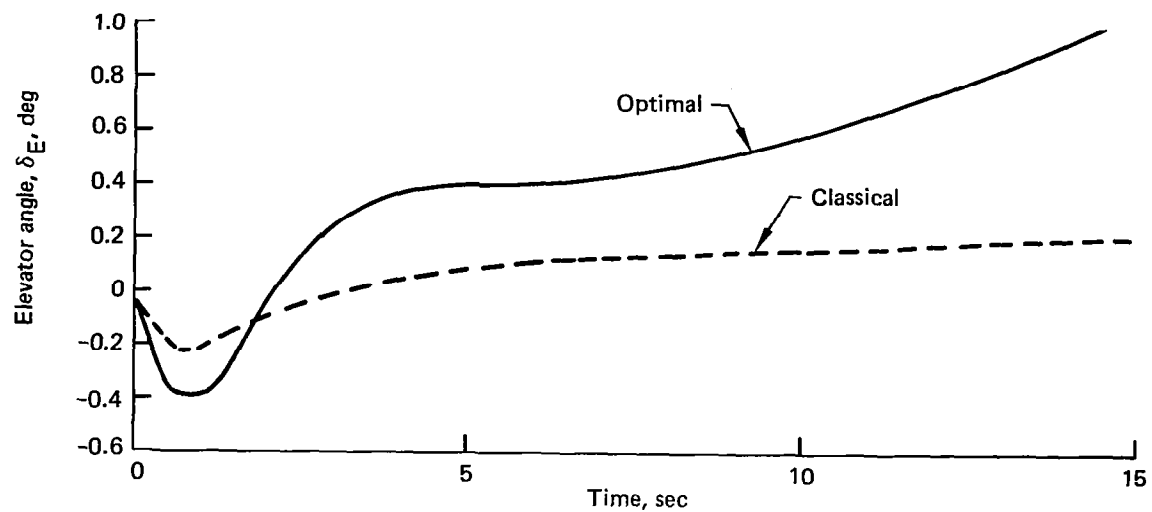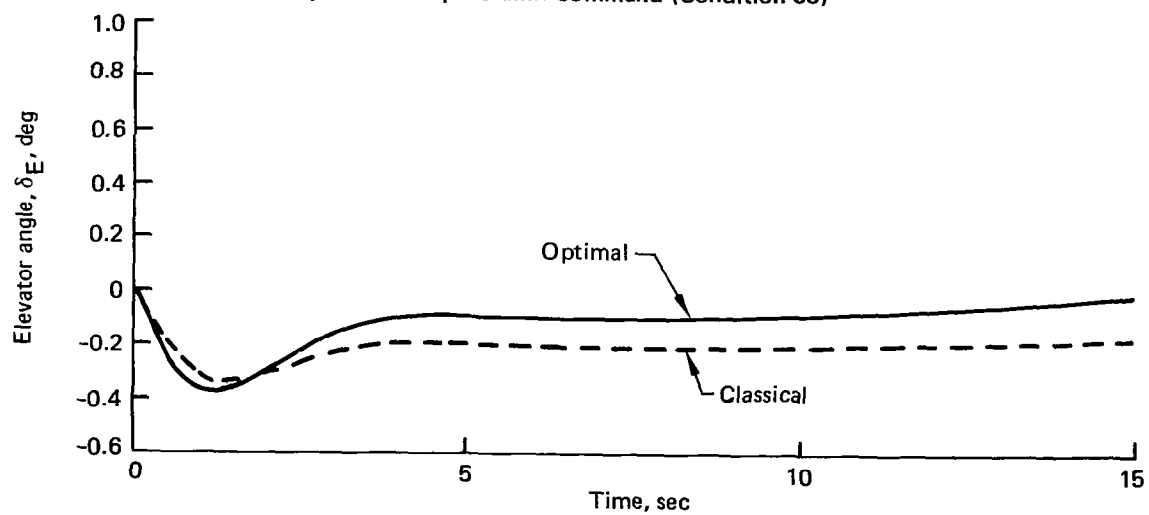*Figure 29. Optimal and Classical System Response to Column Input
(Flight Condition 58)*

Figure 30. *Optimal and Classical System Response to Column Input (Flight Condition 97)*

(a) Elevator Response to Step Column Command (Condition 58)

(b) Elevator Response to Step Column Command (Condition 97)

Figure 31. Optimal and Classical System Response to Column Input

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IMPLEMENTATION ALTERNATIVES

Anticipated Technology Developments and ACT System Alternatives

The objective of this part of the Advanced Technology ACT Control System Definition Task was to identify an ACT system implementation based on component properties and characteristics expected to be available for a commercial airplane circa 1990. The first phase of this work examined the technology developments in sensors, actuators, computer hardware, and computer software and projected that status to approximately 1990. The second phase defined three alternative systems with varying degrees of risk and qualitatively assessed them. The final phase selected a 1990 implementation of ACT and performed reliability and cost-of-ownership analyses for that system.

The sensor survey addressed air data, attitude, angular rate, and acceleration sensors. It was concluded that air data should be obtained from the airplane's triplex digital air data system and the attitude signals from the triplex inertial reference system. Based on examination of several present and evolving concepts for angular rate sensors, the ring laser gyro was recommended. Center-of-gravity acceleration is best obtained from the inertial reference system output signals. Wing-mounted accelerometers should be piezo-resistive strain gages because of their relatively low cost and high dynamic response.

Ultrareliable high-speed central processing components are expected in the late 1980s, resulting from very-large-scale and very-high-speed integrated circuit developments, with associated reductions in chip counts and connections between chips. Size, weight, and power requirements of the system's computers will no longer be a significant consideration and costs will be reduced to relatively unimportant levels. Standardization of instruction sets should permit efficient and reliable flight controls software development.

Actuation concepts were reviewed and compared to the requirements. It was concluded that, except for the flaperons, conventional hydraulic actuation concepts should be applied for a 1990 ACT airplane.

Three alternative advanced technology ACT system configurations, characterized as having low, medium, and high risk for a circa 1990 implementation, are shown in Figure 32. The high-risk system (fig. 32(a)) capitalizes on recent and projected advances in self-testing digital circuitry and in integrated circuit technology. The computational element, consisting of four self-checking computer modules of multiple microprocessors, builds on the concepts used in the fault-tolerant multiple processor (FTMP) and software-implemented fault tolerance (SIFT) architectures. Each module is 100% self-checking and does not require cross-channel comparison. The computers run asynchronously, and the system relies on ultrareliable self-checking bus adapters and controllers.

The medium-risk system (fig. 32(b)) uses multiple microprocessors, operating asynchronously, in each computing channel. Serial digital data busing is used extensively for both sensor and actuator interfaces. The principal objectives of this design were to create an increased number of success paths for flight safety and dispatch reliability and to reduce software complexity and preparation costs.

The low-risk system (fig. 32(c)) follows the developments of the 1970s, with frame-synchronized computers. Data are exchanged between the redundant computers by dedicated serial buses. Computations are identical among computers. Sensor and servo interfaces are primarily analog, and only moderate technology growth is assumed.
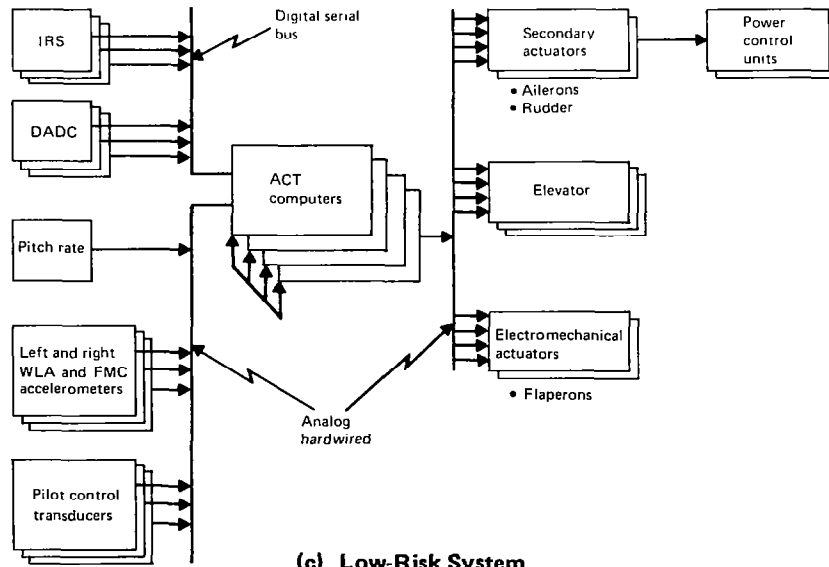
(a) High-Risk System

Quadruple system bus
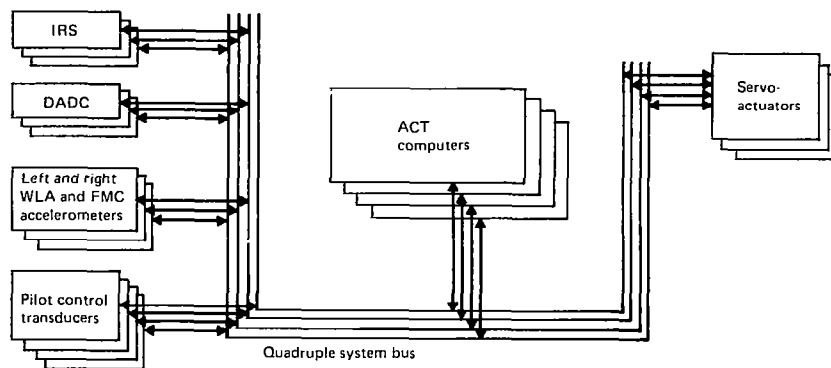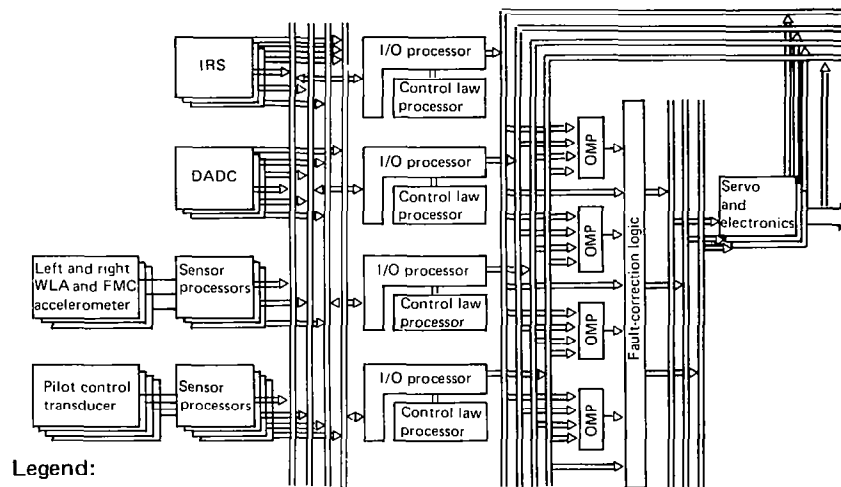
Legend:

OMP   output monitor processor

(b) Medium-Risk System

(c) Low-Risk System

Figure 32.   Advanced ACT System Alternatives

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Alternative System Comparison

Key characteristics of the three alternative systems are shown in Table 6. The low-risk system could best be characterized as current technology, requiring relatively complex software and using serial digital data buses for only the inertial reference system and digital air data computer outputs, with all other sensors hardwired (analog) to the ACT computers. The computers are frame synchronized with self-check and bit-by-bit comparison monitors. Finally, the system assumes the presence of an analog backup system.

The medium-risk system uses extensive busing and multiple microprocessors and assumes that projections of software and integrated circuit technologies have a reasonable probability of being available for system realization by 1990. The sensor set is the same as the low-risk system set, except that no separate pitch-rate sensor is provided. A Luenberger observer is used to estimate pitch rate if two of the three identical inertial reference system rate gyros fail. The computer architecture differs significantly from the low-risk system in the area of multiple microprocessors operating asynchronously. This is expected to lead to more simplified software.

The high-risk system uses the same sensor set as the medium-risk system set, with data input on a common serial digital bus. It has a single universal quadruple bus system instead of the separate bus systems present in the medium-risk and low-risk systems. Finally, the quadruple computer system is composed of self-checking computing modules.

Table 6. Alternative System Comparison

Characteristics	System features		
	Low risk	Medium risk	High risk
● Sensor set	● Three IRSs ● Three DADCs ● Three sets of acceler-ometers for WLA and FMC ● Four pilot input transducers ● One pitch-rate sensor	● Same as the low-risk system without pitch-rate sensor	● Same as the medium-risk system

● Sensor input approach
  ● IRS }
  ● DADC }
  ● Others
	● Serial digital bus to the ACT computer
	● Hardwired analog to the ACT computer
		● Serial digital bus to I/O processor	● On common serial digital bus

● Failure management
  ● Critical functions
 	
  ● Crucial functions
	● Majority vote and com-parison monitoring
	● Same with fourth pitch-rate sensor
		● Same as the low-risk system
		● Same with Luenberger observer to estimate q from vertical accelera-tion and other signals
			● Same as the low-risk system
			● Same as the medium-risk system

● Bus structure	● Two bus systems
	  ● ARINC 429 from IRS and DADC to ACT computer
	  ● Serial digital data exchange between computers
		● Three bus systems
		  ● Quadruple sensors to I/O processor
		  ● Quadruple I/O proces-sor to output monitor processor
		  ● Triplex, output monitor processor to servos
			● One universal quad-ruple bus system
			  ● Self-checking

● Computer system
  ● Redundancy
  ● Architecture
 	
  ● Synchronization
● Failure management
 	
● Analog backup
	● Quadruple
	● Uniprocessors
	
	● Frame synchronized
	● Self-check and bit-by-bit comparison monitor
	● Yes
		● Quadruple
		● Multimicroprocessors
		  ● Sensor
		  ● I/O
		  ● Control law
		  ● Output monitor
		  ● Servo
		● Asynchronous
		● Output monitor pro-cessor, comparison
		● No
			● Quadruple
			● Self-checking comput-ing modules composed of multiple processors
			
			● Asynchronous
			● Completely self-check-ing, no comparison
			● No

● Servos and actuators
  ● Servo loop electronics
  ● Command output approach
 	
  ● Failure management
	● In ACT computers
	
	● Hardwired analog
	
	● Monitored in ACT computer
	● Hardwired fault correction
		● In dedicated servo-microprocessor
		● Serial digital buses
		  ● Quadruple to OMP
		  ● Triplex OMP to servo
		● Monitored in OMP
		● Fault correction via serial bus
			● Incorporated in multiprocessor
			● On common serial digital bus
			
			● Monitored in ACT computer
			● Fault correction via bus

● Software characteristics	● Complex, 1980 technology	● Simplified, segmented into microprocessors by function; reduced redun-dancy management required	● Simpler because of self-checking autonomous channels, highly reliable through advanced verifi-cation and validation
● Reliability assessment (probability of failure during 1-hr flight)*	● 4×10^{-12}	● $< 10^{-12}$	● Not assessed

*Reliability assessment is for sensing and computation (actuation excluded) and assumes software reliability and coverage equal to 1.0.

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1990 ACT System Architecture

A derivative of the medium-risk system described previously was selected for further evaluation and cost-of-ownership analysis. This system is called the 1990 ACT System. The 1990 ACT System uses redundant buses for sensor-computer and computer-actuator interfaces, with all sensor data available to all computing channels. The computing is asynchronous among channels and is compartmented such that separate microcomputers perform input/output (I/O) processing, control law computations, and redundancy management. This avoids the monolithic software structure and results in lower cost for software design, validation, and verification. The sensors and actuators have self-contained electric power supplies and bus interface circuits. The crucial control law computation mode is assumed by the I/O microcomputer if the control law microcomputer fails in that channel. This provides additional redundancy and reliability for the crucial functions.

The 1990 ACT System is integrated; all functions are performed by each of the central set of four ACT computers. Sensors and control surface actuators are shared between functions to the extent allowed by the control laws. The airplane's primary control is fly by wire with all control surface actuators signaled electrically. Figure 33 shows the system architecture.

The ACT Maintenance and Display Computer, warning electronics module, and dedicated ACT panel interface with the computers by the same set of four buses associated with the surface actuators. Each sensor contains bus interface electronics, including an analog-to-digital (A/D) converter, an asynchronous serial I/O communication circuit, and the logic necessary to handle data requests and transmissions.

Each hydraulic servoactuator contains electronics to receive and decode serial data, convert the commands to an analog signal, demodulate the feedback signals required for servo control, and close the servo loop.

The probability of total function loss of the crucial PAS function was estimated to be 1.7×10^{-12} during a flight of 1 hr, assuming software reliability and coverage equal to 1.0. The probability of loss of any critical ACT function was estimated to be 2.7×10^{-7}. Both estimates are more than one order of magnitude less likely than the goals of probability of loss of crucial function to be less than 10^{-9} and probability of loss of critical functions to be less than 10^{-5}.

Airplane sensors

Quadruple sensor bus Quadruple actuator bus

Integrated actuators

*Digital air data computer

*Inertial reference system

ACT computers

ACT Maintenance and Display Computer

*Warning electronics module

ACT discrete display

Right wing WLA accelerometer

Left wing WLA accelerometer

Right wing FMC accelerometer

Left wing FMC accelerometer

Pilot inputs →

Pilot control transducers pitch, roll, and yaw

Left outboard aileron—outboard segment actuator

Left outboard aileron—inboard segment actuator

Left inboard aileron actuator

Lower rudder actuator

Left elevator actuator

Servodrive electronics unit

Servodrive electronics unit

Servodrive electronics unit

Servodrive electronics unit

Right outboard aileron—outboard segment actuator

Right outboard aileron—inboard segment actuator

Right inboard aileron actuator

Upper rudder actuator

Right elevator actuator

Right outboard flaperon electromechanical actuator

Left outboard flaperon electromechanical actuator

Right inboard flaperon electromechanical actuator

Left inboard flaperon electromechanical actuator

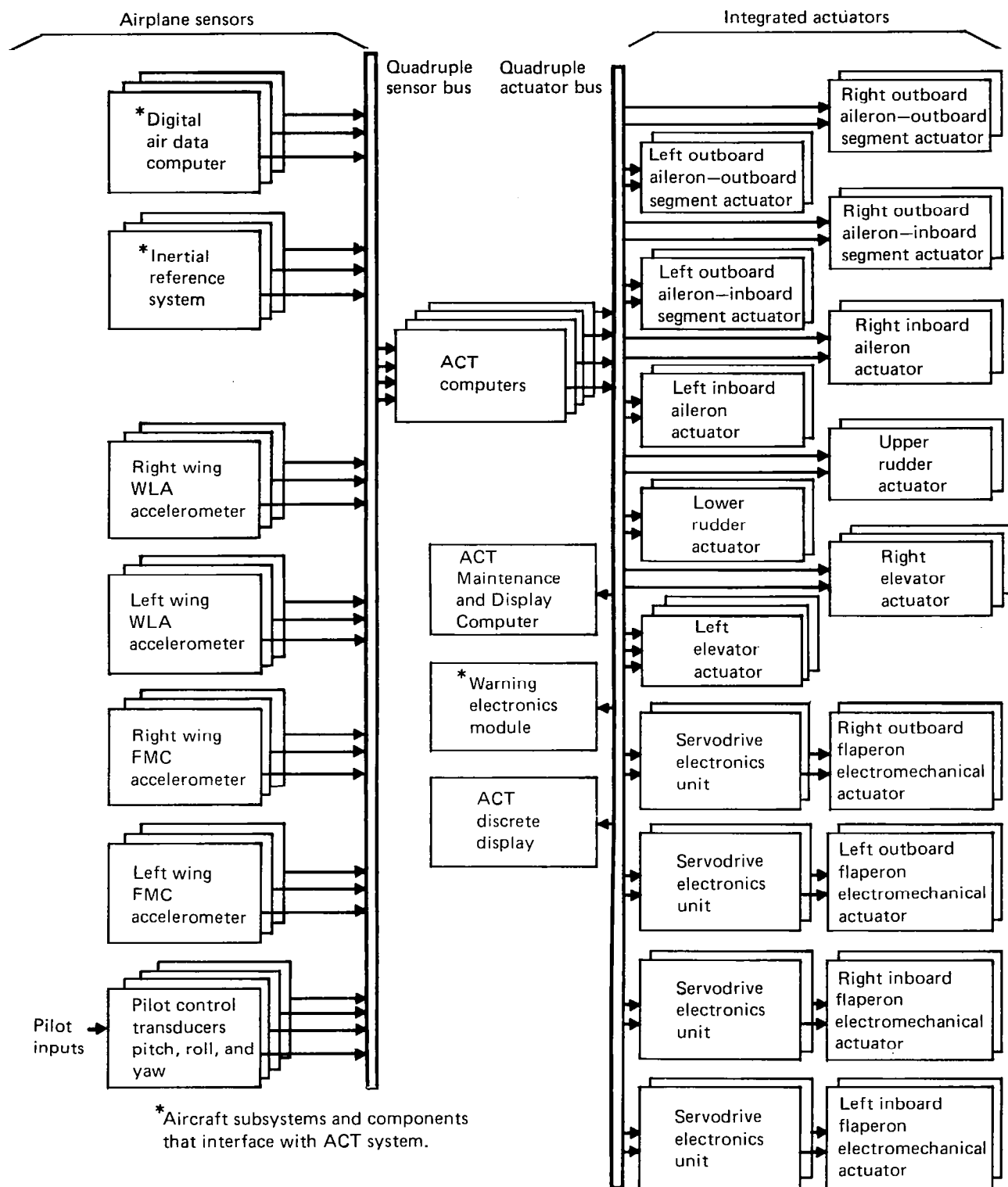*Aircraft subsystems and components that interface with ACT system.

Figure 33. 1990 ACT System Architecture

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Cost-of-Ownership Evaluation

Cost of ownership for the 1990 ACT System was analyzed and compared with the current technology systems. Because cost of ownership depends upon airplane configuration and the most complete data set was available for the Initial ACT Configuration (refs 2 and 3), the external aerodynamic characteristics, active control functions, and surfaces of that airplane were assumed. Thus flaperons were not included in the cost-of-ownership evaluation. The analysis for the 1990 ACT System was performed based on increments from the current technology Selected System discussed previously.

Basically, the 1990 ACT System differs from the Selected System as follows:

● All mechanical connections and components connecting the cockpit flight controls to the actuator servovalves are deleted.

● Mechanical servo feedback to hydraulic power control unit servovalves is deleted.

● All ACT secondary servos and the two FMC servos are deleted.

● Four flight control computers replace the three ACT Primary Computers and four Essential PAS Computers of the Selected System.

● Sensors peculiar to the Selected System are replaced by the sensors that can communicate directly to the digital data bus.

● All autopilot and yaw damper actuators are replaced by primary fly-by-wire actuators.

The cost-of-ownership parameters shown in Table 7 are based on estimates of line replaceable unit cost, weight, and maintenance costs for the 1990s. The most important differences between the Selected System and the 1990 ACT System are the significant reductions in incremental airplane purchase cost and airplane weight. Approximately one-quarter of the weight reduction and about one-half of the incremental airplane price reduction would be available to the Selected System through implementation of fly by wire. The balance of the savings stem from the advanced technology incorporated into the 1990 ACT System.

Most of the cost reduction is due to deleting thousands of parts inherent in the mechanical transmission of pilot's control signals and deleting autopilot actuators. The weight reduction is primarily derived from deletion of mechanical flight controls, with significant contributions from the autopilot actuator deletion and the substitution of a lower weight fly-by-wire surface control actuator. The weight savings lead to significant increases in the fuel saving per flight hour (table 7).

The most significant result of this work, as shown in Table 7, is the improvement of the 1990 ACT System relative to the current technology Selected System. Of special interest is the approximately 42% increase in return on incremental investment (1990 ACT System relative to the Selected System) and the approximately 30% reduction in the payback period to the airline.

Table 7. Cost-of-Ownership Results for Various ACT Systems

Parameter incremented	Current technology				Advanced technology
	Integrated	Segregated	Selected	Selected + pitch FBW	1990 ACT
Aircraft purchase cost per aircraft (in 1000 dollars)	274	390.2	297.1	207	98.8
Maintenance manual cost per 30-aircraft fleet (in 1000 dollars)	21	31.4	26.1	26.1	54.7
Test equipment cost per 30-aircraft fleet (in 1000 dollars)	22.5	44.9	33.6	33.6	10.0
Spare inventory initial cost per 30-aircraft fleet (in 1000 dollars)	250	356	271.1	271.1	221.1
Maintenance cost per aircraft flight hour (in dollars)	4.18	4.91	4.22	3.98	-0.59
Departure delay and cancellation cost per aircraft flight hour (in dollars)	0.54	0.45	0.19	0.12	0.54
Change in system weight relative to Integrated ACT	0	+114 kg (+252 lb)	+14 kg (+30 lb)	-156 kg (-345 lb)	-629 kg (-1386 lb)
Fuel saving per flight hour at 863 km (466 nmi)	160 kg (352 lb)	146 kg (322 lb)	160 kg (352 lb)	172 kg (379 lb)	212 kg (468 lb)
Payback period in years	2.83	4.14	2.98	2.02	< 2.0
Return on incremental investment to airline	25.1%	22.1%	24.6%	27.6%	34.9%

CONCLUDING REMARKS

The results to date of the IAAC Project show that the concept of an ACT airplane designed as such from the outset will indeed yield important savings in block fuel over a similar commercial transport without active controls. The results of the Current and Advanced Technology ACT Control System Definition work summarized in this report show that it is feasible to support such an active controls airplane with a control system that meets all reliability and availability requirements (assuming software reliability and coverage equal to 1.0). The results also show that this can be done at a cost that provides an attractive return on investment for the airline. The ACT systems will become even more attractive if fuel prices continue to inflate as experienced since early in the 1970s.

The Current Technology ACT Control System Definition Task had two primary objectives. The first objective was to define a digital ACT control system architecture using flight control system elements currently in use or considered acceptable for commercial transports. The second objective was to identify the major concerns and then resolve issues related to the use of such a control system. Three control systems (Integrated, Segregated, and Selected) were designed, and all met the reliability requirements. The Segregated System is predicted to be the most reliable, followed in order by the Selected System and then the Integrated System. The Integrated System with its single set of redundant digital control computers is the most efficient of the three systems; i.e., it satisfies function and reliability requirements at the lowest cost. The Segregated System failed to show the expected major improvements in reliability and exhibited unacceptably higher costs. The Selected System shows a decided reliability improvement over the Integrated System with only a small increase in cost.

The major concerns that arise from review of these results are system complexity and the ever-present question of system reliability in the operational environment. Hardware reliability predictions are based on consistently conservative choices in values for system elements and in the techniques and system representations used in the reliability calculations. Although the absolute values of the resulting reliability predictions may be suspect, their use as one of several figures of merit is considered well founded.

There is no generally accepted method to prove software reliability equal to the required level. However, extensive experience in engineering real-time digital control systems for airplanes and spacecraft has shown that a process that begins with careful functional analysis and leads through requirements, design, coding, verification, validation, exhaustive testing, configuration control, and careful documentation can produce highly reliable real-time control software. Therefore, it is concluded that the Selected System can be implemented using currently available technology and software design processes, although the ultimate production and certification of these systems will require significant additional experimental and confidence-building work.

The objectives of the Advanced Technology ACT Control System Definition Task were to (1) determine the benefits of synthesizing ACT control laws using optimal control law estimation theory, (2) determine the effects of actuation system nonlinearities on gust-load alleviation and flutter-suppression effectiveness, and (3) identify advanced flight control system implementation concepts as an alternative to the current technology implementation previously discussed.

Analysis procedures were developed that offer systematic methods for selecting proper control surfaces, actuation bandwidths, and sensor locations for specific ACT function

performance. The design procedures based upon time-domain optimal control theory offer a direct and systematic method to derive multiloop control laws that satisfy typical ACT design requirements.

The medium-risk 1990 technology ACT system design met the objectives of providing the same ACT functions with suitable reliability at improved cost. The system is a quadruply redundant integrated system combined with fly-by-wire primary controls in all three axes. Its architecture is strongly oriented toward digital buses and multiple microprocessors, using quadruple input buses coupling digital sensors to the four central control computers and quadruple output buses feeding the servoelectronic units that incorporate digital-to-analog conversion. The system exhibits very attractive predicted return on incremental investment and appears feasible in the 1990 time period. The incorporation of fly by wire was a very large part of the cost benefit predicted for these advanced systems.

The encouraging results of this control system work emphasize the desirability of proceeding with the planned laboratory tests and flight demonstrations of the IAAC Project Plan (ref 1). The laboratory tests and flight demonstration are necessary to reduce the technical risks of committing a commercial transport program that will depend upon ACT to a level commensurate with current commercial practice. The current plan is to proceed with the IAAC Project according to the IAAC Project Plan (ref 1).

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15. Supplementary Notes

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Summary Report

16. Abstract

This report summarizes the Current and Advanced Technology ACT Control System Definition Tasks of the Integrated Application of Active Controls (IAAC) Technology Project within the Energy Efficient Transport Program. These system definitions support the Initial ACT Configuration, Wing Planform Study and Final Configuration Selection, and Final ACT Airplane Configuration with data to validate the assessment of their energy efficiency. Study ground rules allowed the current technology system to use only elements fully demonstrated and available in 1980; the advanced technology system represents technology of the 1990s era. The systems mechanize six active control functions: pitch-augmented stability, angle-of-attack limiting, lateral/directional-augmented stability, gust-load alleviation, maneuver-load control, and flutter-mode control. The redundant digital control systems defined meet all function requirements with required reliability and declining weight and cost as advanced technology is introduced. They indicate the advisability of demonstrating key system elements in laboratory and flight test.

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